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K.W.

FINAL REPORT

EVALUATION OF ALTERNATIVE DESIGNS FOR SOIL MOISTURE SENSING DEVICES

by

Kendrick W. Lentz, Jr.

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EVALUATION OF
SOIL MOISTURE
THERMOCOUPLE PROBE
CONCEPTS
~~technique~~
measurement
humidity

EVALUATION OF ALTERNATIVE DESIGNS FOR SOIL MOISTURE SENSING DEVICES

1.0 Introduction

Accurate measurement of soil moisture matric potential, or the energy state of soil water, is required for meaningful data collection in reforestation studies by the U.S.D.A. Forest Service. In current use are dual junction thermocouple psychrometer probes which require individual calibration to yield accuracies which are marginal at best.

This study was undertaken to investigate new sensor designs and to determine the best approach to developing accurate, low-cost sensors which could be extensively interchanged without recalibration. The availability of such a sensor would greatly facilitate large scale forestation studies as well as be a valuable tool to the agricultural community.

Section 1 develops the measurement requirements which the new sensor must meet. Section 3 reviews background material and past approaches to the soil moisture potential measurement problem. Currently available soil moisture equipment and capabilities are discussed.

Section 4 presents a compilation of new sensor designs and concepts which were developed in a roundtable discussion of engineers. Section 5 analyzes the more promising concepts, and Section 6 presents the evaluation study conclusions and recommendations.

2.0 Definition of the Measurement Problem

2.1 Soil Moisture - General

A 1976 investigation (1) by the U.S.D.A. Forest Service into the environmental impact of timber harvesting indicated that improved monitoring methods and equipment were necessary. In terms of overall importance, soil moisture was ranked as the most important parameter needing quantification. It was recommended that an environmental monitoring package be defined which was capable of monitoring 35 parameters, of which soil moisture potential was one of the important factors.

Soil moisture potential represented one parameter for which commercially available sensors were unsatisfactory. The current study was undertaken to identify and evaluate new sensor designs which might satisfy the soil moisture potential measurement requirement.

2.1.1 Soil Moisture Potential

Soil moisture potential is an expression of the potential energy of soil water relative to free water at atmospheric pressure and at the same temperature as the soil. Definition of soil moisture potential over an extended land mass allows the tendency of soil water to flow to be calculated, as the water seeks to move from a higher to lower energy state. Superposition of plants and vegetation, each with its own characteristic moisture potential, on the potential energy "map" shows the overall availability of soil water for plant growth.

Total soil water potential, ϕ_t, consists of three parts:

$$\phi_t = \phi_g + \phi_p + \phi_o \qquad (1)$$

where: ϕ_g = Gravitational potential, or the potential energy of soil water due to elevation against gravity.

ϕ_p = Pressure potential, or "matric" potential, which is the quantity of primary interest here.

ϕ_o = Osmotic potential, occuring across a semi-permeable membrane, and primarily of interest in the interaction of plant roots with the soil.

Pressure, or "matric" potential is negative in all cases except that of saturated soil under positive hydrostatic head. (Say at the bottom of a lake, etc.) Because this pressure is negative with respect to free standing water, soil moisture matric potential is also commonly referred to as "suction" or "tension". Thus soils with a high (negative) moisture potential exhibit stong tendencies to "suck" up soil water. Very dry soils have high (negative) matric potential.

Matric potential is manifested by two basic phenomena. The first is capillarity, whereby the pores in the soil take up water by virtue of its surface tension. The second is adsorption, whereby soil water adheres to soil particle surfaces. In general, stronger capillarity effects will be observed in soil with finer pore sizes or soil which has been compacted. Stronger adsorption effects will generally be realized in clay-like soils as opposed to sandy soils.

Soil moisture matric potential can be expressed as energy per unit mass (joules/kilogram), energy per unit volume (pressure), or energy per unit weight (head). Common pressure units used are bars, and these are the units of soil moisture potential used throughout this report.

A comprehensive description of the state of water in soil can be found in Ref. (2), Soil and Water, by Hillel.

2.1.2 Soil Moisture Content

Soil moisture content, or "wetness" is a measure of the volume or mass of water in a given volume of soil. It is not equivalent to soil moisture potential, and no universal correlation exists between the two quantities.

Figure 1 shows a general relationship between wetness and matric potential for two extremes in soil texture. For a given absolute water content, a clay-like soil has a higher (negative) matric potential than does a sandy soil. Stated alternatively, a given volume of clay-like soil has a stronger affinity for a fixed amount of water than does a similar volume of sandy soil.Figure 1 indicates that a sensor which measures soil wetness would have to be calibrated over its entire range to measure soil moisture matric potential, and then uniquely for each type of soil to be studied.

Figure 2 shows a further complicating phenomenon of "hysteresis" in the relationship between soil moisture content and soil moisture potential. A given sample of soil exhibits a different relationship in sorption (moisture increasing) than it does in desorption (soil drying out). If it were possible (and practical) to measure soil moisture potential with a calibrated soil wetness sensor, a single reading would not be sufficient. Multiple (or continuous) readings would be required to establish which leg of the calibration curve was appropriate.

It is unfortunate from a measurement point of view that a universal, single valued relationship between soil moisture content and soil moisture potential does not exist, since in practice, it is easier to instrument and accurately monitor soil moisture content.

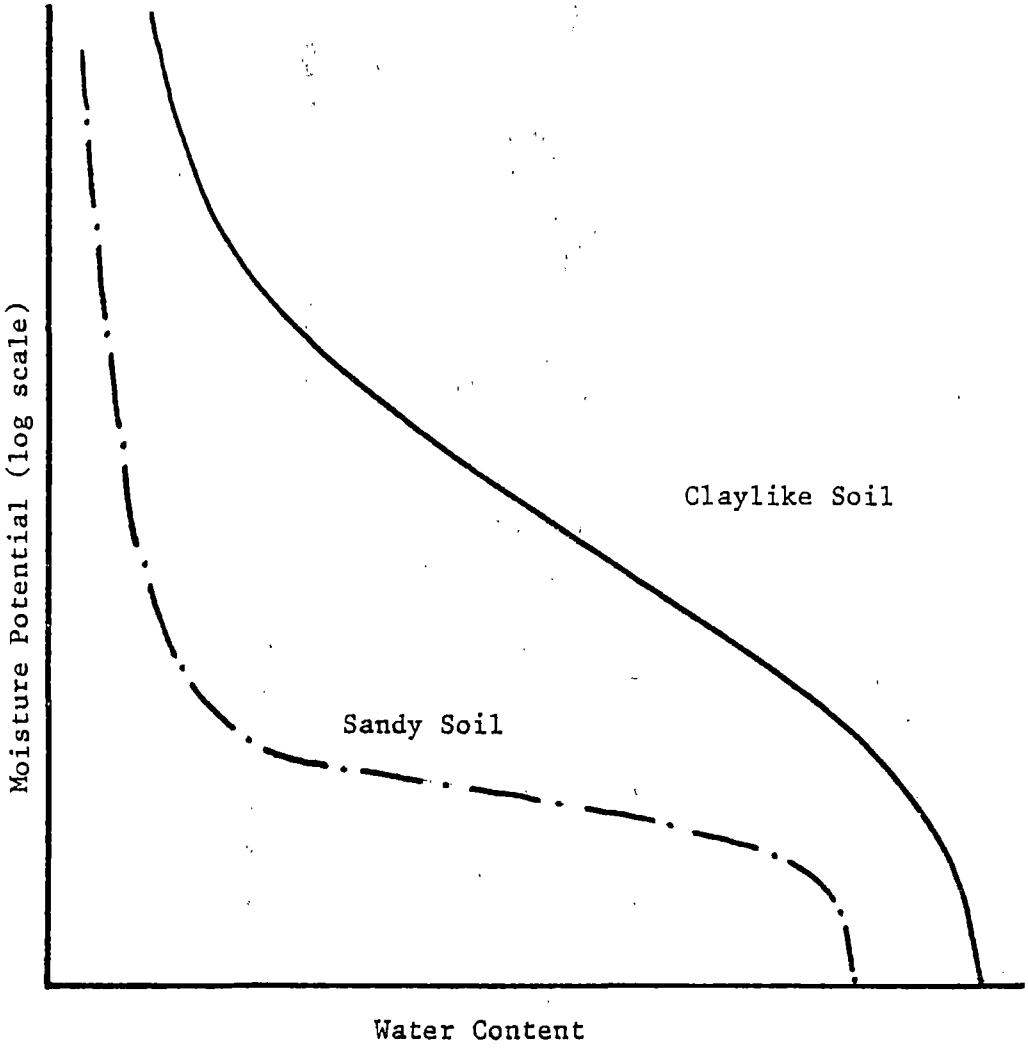


Figure 1

Relation Between Water Content
And Moisture Potential

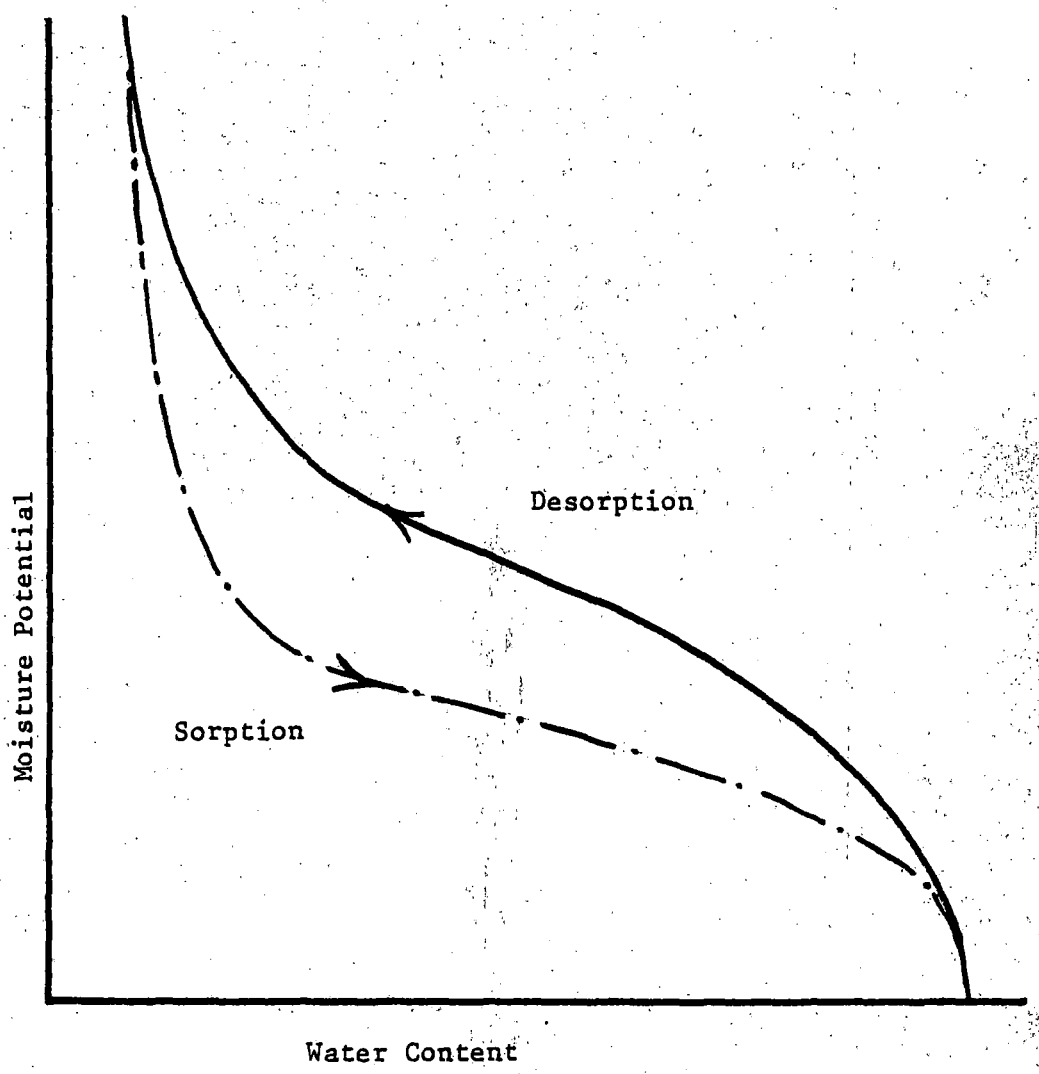


Figure 2

Hysteresis in Relation Between
Water Content and Moisture Potential

2.2 Measuring Soil Moisture Potential

Two methods widely used in measuring soil moisture potential are: (1) the tensiometer, and (2) the dual junction thermocouple psychrometer. The tensiometer is generally not useful for potential measurements exceeding 0.8 bar, nor is it particularly adaptable to in situ monitoring. Descriptions of the tensiometer equipment and methods can be found in references (2) and (3).

Psychrometric methods utilize measurement of the relative humidity of air in equilibrium with the soil sample as an indirect measurement of soil moisture potential.Moist soil will equilibrate at higher relative humidities than will dry soil. Since moist air is a universally consistent two phase system, determination of its thermodynamic potential energy (assuming it to be equivalent to that of the adjacent soil) simplifies the measurement problem in that variations in soil texture, type, chemical content and compaction need not be considered.

Humidity of a volume of air in equilibrium with moist soil is the integrated result of work performed as the water "evaporates" from the soil into the air volume. It is thus uniquely related to the affinity of the surrounding soil for water, or its matric potential. The relationship between matric potential, ϕ , and relative humidity, (r.h.), is:

$$\phi = \frac{R\ T}{V} \ln (r.h.) \qquad (2)$$

where: ϕ = Matric potential (bars)

R = Gas constant = 0.0832 (liter-bars/gm- mole ^{o}K)

T = Ambient temperature (^{o}K)

V = Specific volume of water vapor at T (liters/gm- mole)

r.h. = Relative humidity expressed as a decimal fraction.

Humidity can be measured in several (indirect) ways. An internal U.S.D.A. Forest Service compilation of humidity measurement techniques (4) describes them in outline form, and some of these are evaluated in later sections of this report as to their applicability to the soil moisture potential sensing problem. However, one method, thermocouple psychrometry, is currently in wide use, and appears to be an attractive approach to improved methods and equipment. Psychrometry relates the temperature depression of a "wet bulb" temperature or a "dew point" temperature with respect to ambient temperature.

Relative humidity, or relative activity as it is often called in soil physics, is related to wet bulb and dry bulb (ambient) temperature by the following relation:

$$r.h. = 1 - A \frac{p}{p_s} (T - T_{wb}) \qquad (3)$$

where:
- r.h. = Relative humidity, decimal, at T_{wb}
- A = Psychrometer constant = 6.2×10^{-4} $^{o}C^{-1}$ for a fully aspirated thermocouple (which typical soil moisture sensors are not, since they are buried)
- p = Total pressure = 14.67 psia (nominally)
- p_s = Saturation vapor pressure at wet bulb temperature
- T = Ambient or dry bulb temperature (^{o}C)
- T_{wb} = Wet bulb temperature (^{o}C)

Relative humidity is also related to ambient temperature and dew point temperature by the relation:

$$\ln(r.h.) = - \frac{\Delta H_v}{R} \left[\frac{1}{T_{dp}} - \frac{1}{T} \right] \qquad (4)$$

where: ΔH_v = Latent heat of vaporization of water
= 10,758 cal/mole @ $0^{o}C$ = 10,555 cal/mole @ $20^{o}C$
= 10,246 cal/mole @ $50^{o}C$

R = Universal gas constant = 1.987 cal./mole- ^{o}C

T = Ambient, or dry bulb temperature (^{o}K)

T_{dp} = Dew point temperature (^{o}K)

If psychrometric methods are to be used, then the measured physical quantity is the wet bulb or dew point temperature depression from ambient temperature. In order to quantify the temperature measurement requirements, Tables I and II have been generated.

Table I tabulates saturation pressures and specific volumes of water vapor over the ambient temperature range of 0^{o} to $65^{o}C$. Tables II-a, II-b, and II-c relate matric potential (bars) to relative humidity, wet bulb temperature depression (^{o}C), and dew point temperature depression (^{o}C) at $0^{o}C$, $20^{o}C$ and $50^{o}C$ respectively. Relative humidities are calculated over the range of moisture potential of 0 to -60 bars using Equation (2). Equation (3) is used to calculate wet bulb temperature depression, but it should be pointed out that the "fully aspirated" psychrometer constant was used. Since this will rarely be the case in soil moisture applications, the expected temperature depressions in practice will be somewhat lower. Dew point temperatures were calculated using Equation (4). The humidity and temperature depressions presented in Table II are accurate enough to define matric potential measurement requirements, but are not exact since some approximations were made.

2.3 Measurement Requirements

Recommendations made by U.S.D.A. Forest Service in Ref. (1) determined that soil moisture potential should be:

- Monitored at several depths.
- Two sample points taken daily
- Measurement range 0 to -80 bars
- Measurement accuracy $\pm$1 bar

TABLE I

Saturation Pressure and Specific Volume of Water Vapor Over Ambient Temperature Range 0 - 65° C

Ambient Temperature		Water Vapor Pressure			Specific Volume of Vapor
°C	°F	in.Hg.	psia	mm.Hg.	liter/gm-mole
0	32	0.1803	0.08854	4.5796	0.018001
5	41	0.2576	0.12652	6.5430	0.018001
10	50	0.3626	0.17811	9.2100	0.018001
15	59	0.5035	0.2473	12.7889	0.018012
20	68	0.6903	0.3390	17.5336	0.018035
25	77	0.9352	0.4593	23.7541	0.018057
30	86	1.2527	0.6152	31.8186	0.018080
35	95	1.6600	0.8153	42.1640	0.018113
40	104	2.1775	1.0695	55.3085	0.018136
45	113	2.8293	1.3896	71.8642	0.018181
50	122	3.6420	1.7888	92.5068	0.018214
55	131	4.6474	2.2826	118.0440	0.018259
60	140	5.8812	2.8886	149.3825	0.018304
65	149	7.3840	3.6270	187.5536	0.018360

Source: Keenan & Keyes; Thermodynamic Properties of Steam;, 1st Edition John Wiley and Sons, N.Y. 1964

TABLE II-a

Relation Between Soil Moisture Potential (Bars), Relative Humidity, Wet Bulb Temperature Depression (°C), Dew Point Temperature Depression (°C) at 0°C (32°F)

Matric Potential (bars)	Relative Humidity	ΔT_{wb} (°C)	ΔT_{dp} (°C)
0.0	1.00000	.0000	.0000
- 0.1	.99992	.0008	.0008
- 0.5	.99960	.0039	.0052
- 1.0	.99921	.0077	.0106
- 2.0	.99842	.0154	.0215
- 3.0	.99763	.0231	.0324
- 4.0	.99683	.0309	.0434
- 5.0	.99605	.0385	.0542
- 6.0	.99526	.0461	.0651
- 10.0	.99211	.0768	.1087
- 15.0	.98818	.1151	.1633
- 20.0	.98427	.1531	.2178
- 25.0	.98038	.1910	.2722
- 30.0	.97650	.2288	.3267
- 40.0	.96880	.3037	.4354
- 50.0	.96115	.3782	.5441
- 60.0	.95356	.4521	.6528

TABLE II-b

Relation Between Soil Moisture Potential (Bars), Relative Humidity, Wet Bulb Temperature Depression (°C), Dew Point Temperature Depression (°C) at 20°C (68°F)

Matric Potential (bars)	Relative Humidity	ΔT_{wb} (°C)	ΔT_{dp} (°C)
0.0	1.00000	.0000	.0000
- 0.1	.99993	.0026	.0011
- 0.5	.99963	.0138	.0060
- 1.0	.99926	.0276	.0119
- 2.0	.99852	.0552	.0239
- 3.0	.99778	.0827	.0359
- 4.0	.99705	.1100	.0477
- 5.0	.99631	.1375	.0597
- 6.0	.99557	.1651	.0717
- 10.0	.99263	.2747	.1195
- 15.0	.98896	.4115	.1793
- 20.0	.98531	.5475	.2390
- 25.0	.98167	.6832	.2987
- 30.0	.97805	.8181	.3582
- 40.0	.97084	1.0868	.4775
- 50.0	.96368	1.3537	.5967
- 60.0	.95658	1.6183	.7156

TABLE II-c

Relation Between Soil Moisture Potential (Bars), Relative Humidity, Wet Bulb Temperature Depression (°C), Dew Point Temperature Depression (°C) at 50°C (122°F)

Matric Potential (bars)	Relative Humidity	ΔT_{wb} (°C)	ΔT_{dp} (°C)
0.0	1.00000	.0000	.0000
- 0.1	.99993	.0138	.0014
- 0.5	.99966	.0669	.0069
- 1.0	.99932	.1337	.0137
- 2.0	.99865	.2655	.0273
- 3.0	.99797	.3992	.0411
- 4.0	.99729	.5330	.0549
- 5.0	.99662	.6647	.0685
- 6.0	.99594	.7985	.0823
- 10.0	.99325	1.3275	.1370
- 15.0	.98989	1.9883	.2054
- 20.0	.98654	2.6472	.2739
- 25.0	.98320	3.3041	.3424
- 30.0	.97987	3.9590	.4109
- 40.0	.97325	5.2609	.5476
- 50.0	.96668	6.5531	.6842
- 60.0	.96015	7.8373	.8207

The current study to identify and evaluate new matric potential measurement devices was directed toward the following performance goals:

- Linear output, when buried in soil, over ambient temperature range of 0° to 65°C, over moisture potential range of 0 to -60 bars
- Exhibit matched characteristics among sensors, with between sensor variability limited to ± .25 bar in the 0 to -15 bar range and ± .5 bar above that range.
- Yield a noise free, high quality signal sufficient to be handled by standard operational amplifiers.
- Size goal of 0.25 inch diameter, .75 inch length without leads.
- Reliable and maintenance-free, performing for minimum of two years unattended; free from any contamination.

Reference to Table II indicates that the following physical measurement requirements are necessary to meet the above criteria:

- Relative humidity must be measured to an accuracy of ± .0008 relative humidity units (.08%) at 0°C and .0007 relative humidity units (.07%) at 50°C. for a potential accuracy of ± 1 bar.
- Relative humidity must be measured to an accuracy of .0002 relative humidity units (.02%) to guarantee ± .25 bar interchangeability between sensors.
- If temperature depression is to be used as a measure of humidity, then temperature differences of ± .008 °C must be resolved for a water potential accuracy of ± 1 bar.
- To guarantee interchangeability of ± .25 bar among sensors, a temperature difference of .002°C must be resolved.

The requirements above do not allow for measurement errors due to other sources, such as electrical noise, readout errors, ambient temperature measurement error, and fluctuations in ambient pressure.

3.0 Background Review

This section presents background material compiled during the project to identify new approaches and technologies relevant to the soil moisture potential sensing problem. Table III outlines the general areas reviewed in developing background information.

3.1 Thermocouple Psychrometry

References (5) through (21) describe various thermocouple psychrometer arrangements used to measure soil or plant moisture potential. They are all two junction psychrometers, and are of two general types. The first type requires a water droplet to be placed on the "wet" junction, where it is held until it evaporates by a small diameter cylinder, or loop in the thermocouple junction. This sensor is only applicable to laboratory measurements, since the water droplet must be applied manually. Laboratory sensors are usually placed into a sample chamber, then immersed in a precision temperature bath to assure a stable, precisely known, ambient temperature.

The only type of thermocouple psychrometer used for in situ monitoring is the "Spanner" or "Peltier" psychrometer. Here, a small (5 - 50 ma) current is applied to the wet junction, thereby cooling it by the Peltier effect (thermoelectric cooling). When the thermocouple junction cools below the dew point, water condenses on the junction. When sufficient water is collected on the junction, the current is stopped, and a precision voltmeter is used to measure the thermal emf across both the wet and dry junctions in series. This output (on the order of microvolts) is an indication of the temperature difference between wet and dry bulb junctions, thus of relative humidity. Since the wet bulb temperature depression is dependent on ambient temperature, a reading of ambient temperature must be made - preferrably before the cooling current is applied.

TABLE III

Background Review Target Areas

I. Soil Moisture Measurement Techniques

- Identify promising ideas and technologies never fully developed in past work.
- Develop offshoots or extensions to past approaches.
- Review rejected or unsatisfactory past methods which might be successfully instrumented using state-of-the-art technology.

II. General Humidity, Moisture Measurement Techniques

- Explore alternate applications of psychrometry technique.
- Identify relevant technology as applied to different, but related problems.

III. General Temperature Measurement Techniques

- Identify precision methods which can be utilized in psychrometric measurements.
- Investigate thin, thick film sensor technology.
- Investigate appropriate semiconductor sensor technology.
- Investigate possible applicability of temperature sensitivity of various solid state devices.

IV. Non-Conventional Measurement Technology

- Electro-magnetic
- Electro-optical
- Ultrasonic/Acoustic
- Infrared
- Radioisotope methods (excluding neutron probe)
- Nuclear Magnetic Resonance Techniques

Thermocouple material used in most cases is chromel-constantan (Type E) because at 40 microvolts per ^{o}F (72 $\mu v/^{o}C$) it represents the highest output of all common metallic junction thermocouples.Typical sensitivities obtained in Peltier type psychrometers are around 0.6 microvolts/bar.

Cooling current required to create a satisfactory water droplet on the wet junction depends mainly on thermocouple junction mass. A large junction requires more current to cool it to the dew point, and its larger surface area requires a larger water droplet. Optimum cooling currents and cooling times are determined experimentally for each particular design. Loss of sensitivity results if the wire between wet and dry junctions offers low thermal resistance. Heat transfer between the two junctions lowers the temperature difference being measured. Therefore, extremely small diameter (2 mil or less) thermocouple wire is used.

The air volume for which wet bulb depression is being measured must be large enough so that the condensed moisture does not change the humidity of the air, and so that the heat tranfer into the wet junction does not change the ambient temperature. Since Peltier cooling at the wet junction is accompanied by heating at the next junction (generally located in the sensor), this heat must not be allowed to substantially change the sample characteristics.

Psychrometers currently used in the field by the Forest Service are fabricated in the laboratory, with junctions being welded by means of discharging a capacitor through the junction as the ends are brought together. Each psychrometer must be individually calibrated, and the data derived from a particular sensor must be processed using that sensors particular calibration. It is believed that the fabrication process itself is mainly responsible for this non-interchangability of sensors.

Wescor, Inc. of Logan, Utah markets a dual junction psychrometer for in situ soil moisture potential monitoring with a claimed accuracy of ± .75 bar at -15 bars and ± 3 bars at -60 bars. The sensor dimensions are 0.3 inches in diameter by 1.5 inches long without leads. Figure 3 is a reproduction of the Wescor soil psychrometer specification sheet, and is presented as a baseline example of commercially available soil psychrometer equipment. Figure 4 shows the Wescor microvoltmeter which provides Peltier cooling current and thermocouple reference junction for ambient temperature measurement as well as the psychrometer readout. In October 1979, the sensors could be purchased for $16 in small quantities and $12 in large (over 100) quantities. The microvoltmeter could be purchased for $1073.

Several design concepts analyzed in this report include improved psychrometer sensors, thus it is important to keep in mind price and performance of existing hardware.

3.2 Other Soil Moisture Measurement Techniques

References (22) through (24) describe a sensor currently marketed by Moisture Control Systems, Inc. of Findlay, Ohio. These sensors measure soil moisture content by measuring the rate of heat dissipation in a porous material. A heat source, centered inside the porous material in moisture content equilibrium with the soil is activated, and the temperature rise at that point measured. The in-ground portion of the system consists of the sensor (2 inches diameter by 5.5 inches long) and the signal conditioning module (2 inches diameter by 5 inches long). Although the sensor actually measures soil moisture content, it is calibrated to read soil moisture potential in bars digitally. A portable data display unit is available, as is a digital printing data logger. The measurement range is -0.1 bars to -15 bars and an accuracy of ± 50 millibars is claimed. The wetness/potential calibration is based on a desorption cycle, and the inaccuracy due to hysteresis was not ascertained.

PCT-55 and PST-55
Soil Hygrometer/Psychrometer
For Water Potential Measurements *(In Situ)*

NEW IMPROVEMENTS
Removable thermocouple shield* permits inspection and cleaning.
* Patent pending

This proven transducer is used in research programs throughout the world. The recent advent of the dew point method of measurement allows it to be used as a thermocouple hygrometer with improved accuracy and convenience for the researcher.

FEATURES

- Controlled junction size and chamber geometry for consistant performance
- Internal connections gold plated for low corrosion
- Copper-constantan thermocouple located at the base of the transducer
- High sensitivity
- Tested individually for: cooling coefficient TT_v, leaks, cleanliness and sensitivity
- Individual calibration curve provided with each unit

SPECIFICATIONS

PSYCHROMETER OUTPUT: 0.47 microvolts/Bar ± 5% at 25° C (may be individually calibrated by the user to closer tolerances).
HYGROMETER OUTPUT: 0.75 microvolt/Bar at 25° C
TT_v : 40 microvolts minimum (8 milliamps, 25° C)
RANGE: TT_v ÷ 0.75 Bars at 25° C (-53 Bars with TT_v = 40 microvolts)

TYPE DESIGNATION

Specify type PCT-55 (ceramic shield) or type PST-55 (exclusive Dutch weave stainless steel screen) and 1.5 or 3 meter lead length by dash no.
Example: PCT-55 – 5 (1.5 meters)
PCT-55 – 10 (3.0 meters)

CHROMEL-CONSTANTAN THERMOCOUPLES
Used by researchers for special applications
Made with .0254 mm dia. wire
Type J-5A thermocouple only (no connecting leads or shield) mounted in teflon plug with gold plated connection pins

All Wescor soil psychrometers contain copper-constantan thermocouples for ambient temperature measurement.

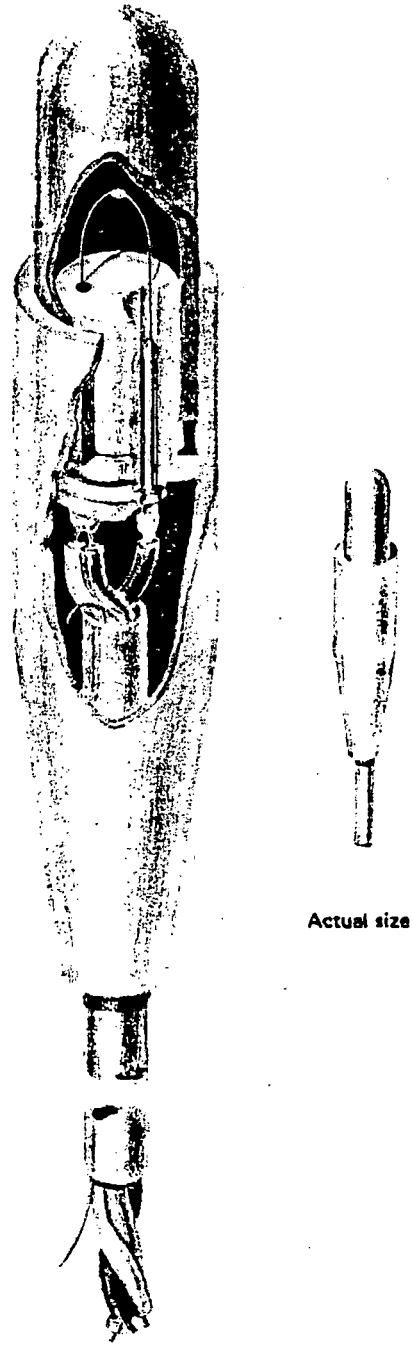


Figure 3

MJ-55 Psychrometric Microvoltmeter

For Water Potential Measurement by the Psychrometer Method

The MJ-55 is a completely solid state, rugged, battery-operated microvoltmeter designed specifically as a readout device for soil and sampling psychrometers. It supplies cooling current to the thermocouple and contains a built-in electronic reference junction for copper-constantan thermocouples. Also, it serves as a versatile general purpose microvoltmeter.

FEATURES

- 150 nanovolt peak to peak noise
- 19 scale ranges from 1 microvolt to 1000 volts
- 1000 hour battery operation
- ±.5° C reference junction stability
- recorder output

SPECIFICATIONS

RANGE: ±1 microvolt full scale to ±1000 volts on zero center meter in 19 overlapping 1X and 3X ranges

ACCURACY: ±1% of full scale recorder output, ±2% of full scale meter exclusive of noise and drift

ZERO DRIFT: less than 0.5 microvolts per 24 hours, typically less than 0.1 microvolt per °C.

METER NOISE: less than 0.03 microvolt rms (0.15 microvolt p-p) on most sensitive range with input shorted

INPUT IMPEDANCE:
100 megohms - 3 volt to 1000 volt ranges
10 megohms - 300 millivolt to 1 volt ranges
1 megohm - 1 microvolt to 100 millivolt ranges

ZERO SUPRESSION: ±25 microvolts

RECORDER OUTPUT: ±1 volt (1 milliamp)

SIZE: 13.3 cm x 21 cm x 17 cm

WEIGHT: 2.7 kg

BATTERIES: 4 Eveready 246 or equivalent
1 Eveready E12N or equivalent

Figure 4

References (25) and (26) review soil moisture content measurement techniques which include soil electrical resistance, gamma ray attenuation and neutron scattering. Neutron scattering is perhaps the most accurate technique for measuring soil moisture content (not potential) in current use. Fast neutrons from a radioisotope source are slowed by collisions with hydrogen nuclei in the water molecules in the soil sample. Slow neutrons are then accurately counted to indicate water content. This method utilizes expensive equipment, requires a radioactive source and is not suited for long term in situ monitoring. The U.S.D.A. Forest Service specifically excluded these systems from consideration here.

References (26) through (31) describe various electrical methods, including soil resistance and capacitance, which indicate soil moisture content rather than soil moisture potential. Reference (32) describes moisture content measurement by means of nuclear magnetic resonance techniques. The apparatus required is complex, and there is difficulty in measuring very dry (low moisture content) samples. This method appears impractical for economical in situ monitoring.

The methods reviewed above measure soil moisture content as opposed to matric potential, but are presented to stimulate consideration of these relatively simple methods <u>if</u> a reliable, accurate, and hysteresis free relation between moisture content and potential can be developed. Can a hysteresis free porous material be developed which equilibrates with moist air, thereby indicating relative humidity? If so, then the relatively simple resistance measurements can be made and related to matric potential.

3.3 Humidity Measurement

References (33) through (36) describe general humidity and moisture measuring techniques and instrumentation. This background material is presented because, as shown in Section 2.2, there is a single-valued

relationship between relative humidity and matric potential. If humidity measurement principles can be applied in the range of 95 to 100% with an accuracy approaching 0.1%, then a viable soil moisture potential sensor might be designed.

Reference (37) describes a thin film aluminum oxide moisture sensor marketed by Panametrics, Inc. of Waltham, Mass. Humidity is indicated by measuring the conductivity of a thin film which varies with water vapor pressure in the adjacent atmosphere. The sensors can be fabricated to very small dimensions. Accuracy near 100% is claimed to be ± 1°C, which, as indicated in Table II is two orders of magnitude larger than the required .01°C (in dew point).

3.4 Temperature Measurement

References (38) through (47) describe fairly recent advances in temperature measurement which should be considered if improved psychrometric techniques are to be developed. As shown in Section 2, temperature discrimination and accuracy to .001 °C is desired for measuring very small wet bulb or dew point temperature depressions. In addition to this degree of accuracy, the devices must also be rugged and stable to withstand two or more years of in situ placement.

Thermistor and other semiconductor sensors are described in References (38), (39), (40) and (45). Thin film and plated thermocouple technology are discussed in References (41), (42), (43), (44), (46) and (47).

4.0 Alternative Water Potential Sensor Designs

The background information of the previous section, as well as copies of the listed references were provided to four individuals. After approximately two weeks of reviewing the background provided, a round-table discussion was held. This Section describes the approaches suggested, and in some cases, contains very little detail.

The alternatives were screened and were subjected to further analysis described in the following Section. After analysis, an evaluation was made as to the most attractive route to follow in future development of advanced soil moisture potential sensors.

4.1 Multiple Junction Thermopile Psychrometer

The U.S.D.A. Forest Service originally proposed a multiple junction thermocouple psychrometer as an approach which would result in improved output signals for the miniscule temperature differences being measured. A series thermopile should multiply the output signal by the number of junction pairs employed.

Two techniques for fabricating the thermopile were suggested. The first was to manually fabricate multiple junctions by welding together a number of short segments of alternating wire types (chromel and constantan), then winding the resulting thermopile around a toroidal, non-conducting core such that the "wet" junctions remained inside and the "dry" junctions outside. Figure 5 shows the thermopile and a conceptual sensor design.

The sensor technique suggested was a thin film, plated thermopile of a design similar to that of Figure 6. Winderman (49) reports a 72 junction radial thermopile with approximately 1 inch outside diameter.

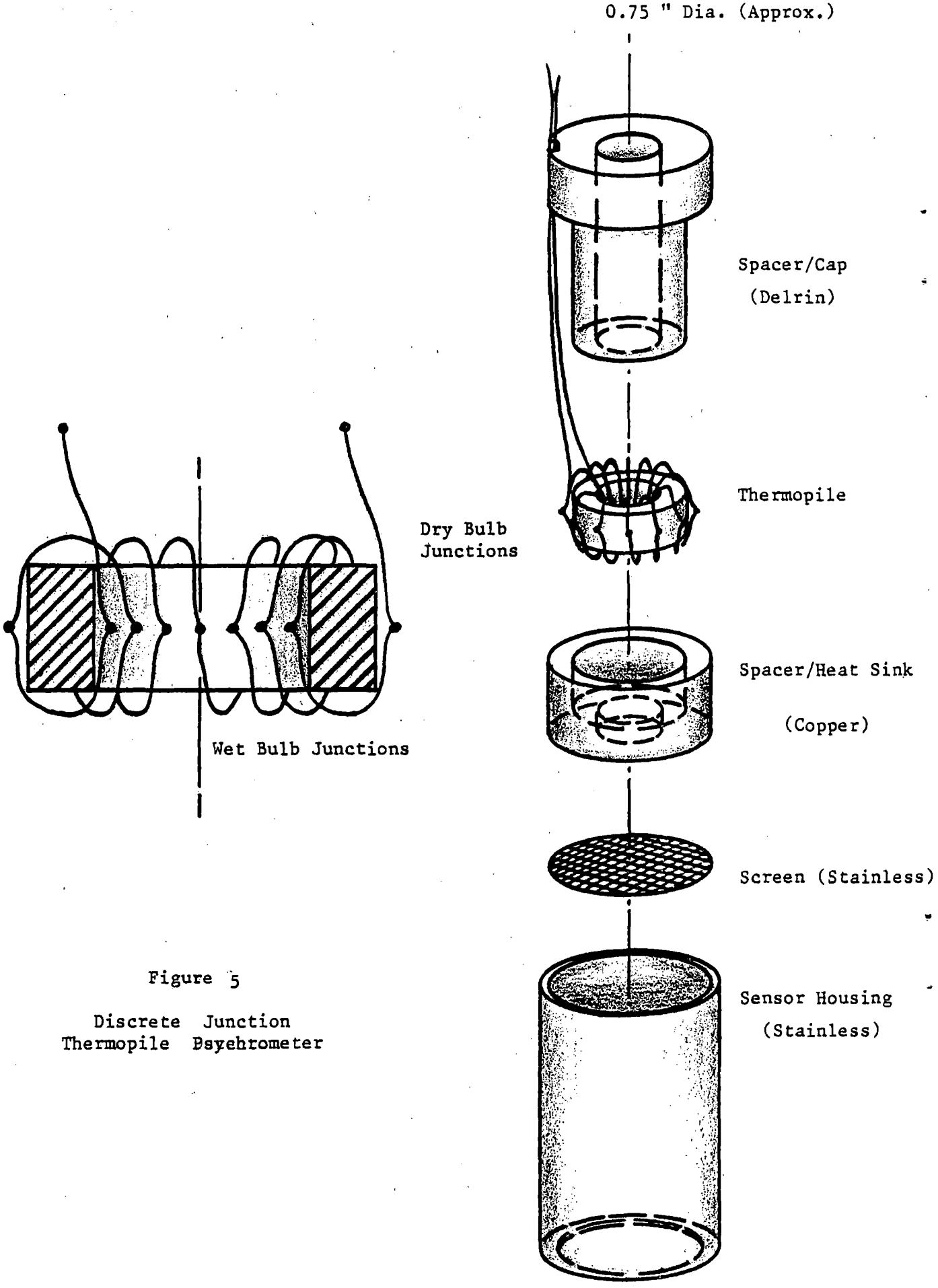
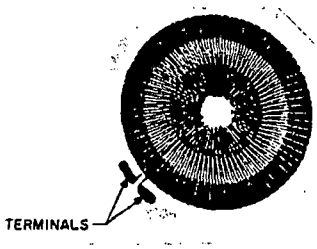


Figure 5

Discrete Junction
Thermopile Psyehrometer



72 Junction Plated Thermopile
(Actual Size)

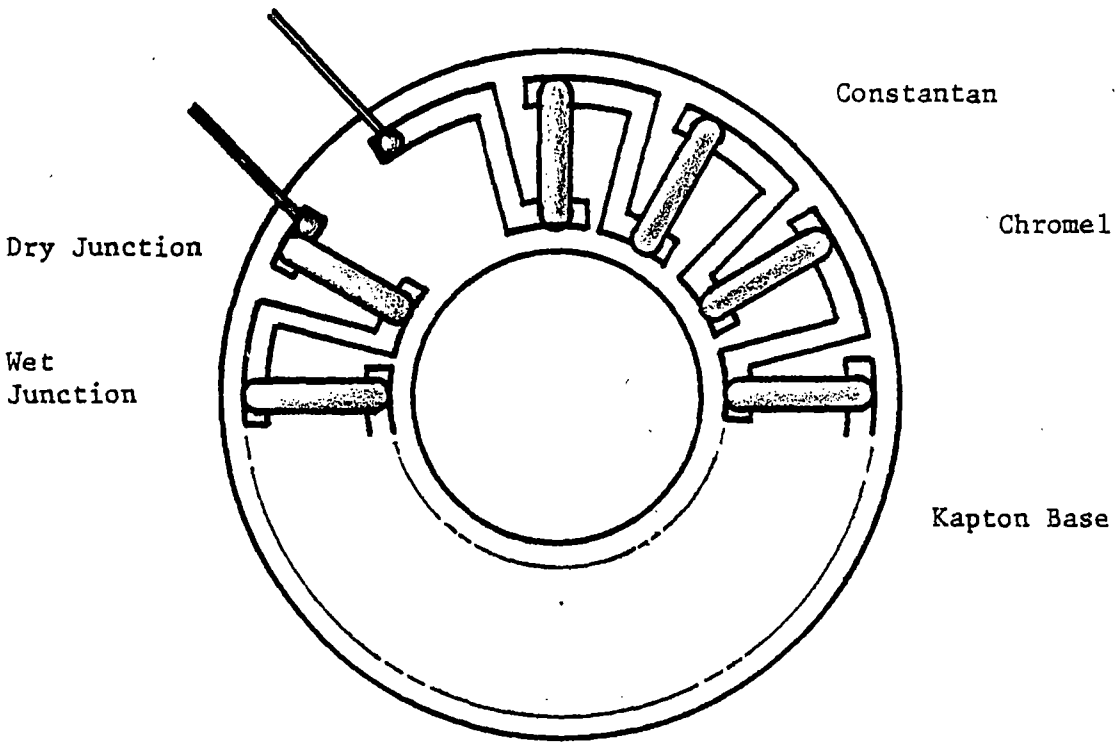


Figure 6

Plated Thermopile

Also reported are 200 junction thermopiles with a sensitivity of 5 millivolts per ^{o}C.

A thin film thermopile sensor would consist of wet junctions toward the center of the sensor (Figure 7) with dry junctions around the outer periphery. It would appear impractical to isolate the wet junctions so that they would be cooled without heating the dry junctions. If power were applied to the thermopile, heat would be "pumped" from the wet junctions to the dry junctions. The dry, or outer, junctions could be heat sinked, to dissipate heat quickly, or allowed to heat up, therefore giving a higher ΔT for a while. The problem with the latter strategy is that errors might result:

1. Heat transfer from the dry junctions would vary with ambient temperature, thus dry junction temperature would decrease faster at lower ambient temperatures. The measured ΔT at a given time after application of cooling current would be a function of ambient temperature.

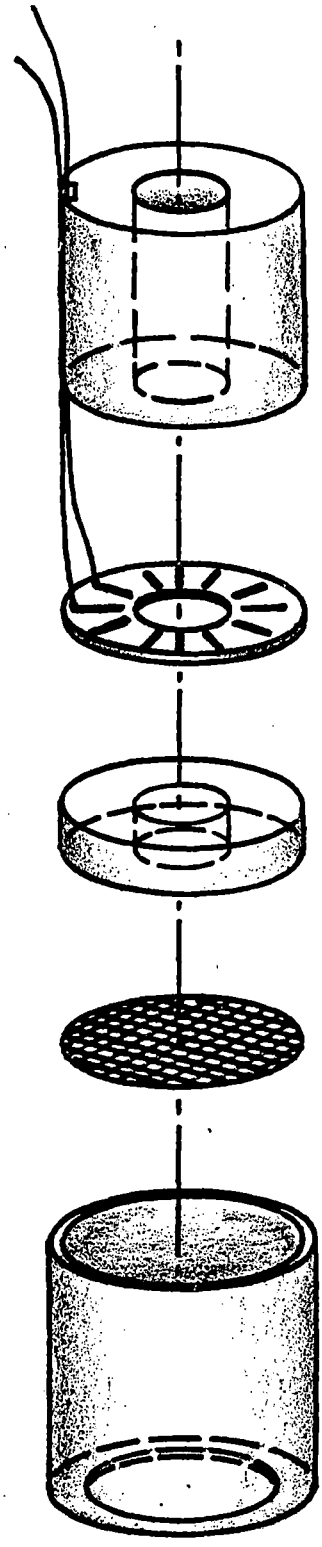
2. Heating of the air space being sampled could affect the measurement if air space was not large enough.

It appears, therefore, necessary to sink the dry junctions to a high relative thermal mass to assure consistent temperature depression.

Ambient temperature would probably be measured with a separate thermocouple. (Not shown in Figure 7).

4.2 Parallel Junction Thermocouple Psychrometer

In discussion of the thermopile psychrometer of the previous Section, it was pointed out that electroplating technology might be used to



Spacer

Ambient Temperature
Thermocouple Not Shown

Thermopile

Spacer/Heat Sink

Screen

Sensor Housing
(Stainless)

Figure 7

Plated Thermopile Psychrometer

fabricate an improved dual junction psychrometer. If the wet and dry thermocouples were replaced with plated junctions greater consistency in sensitivity would be realized, but output would not be improved.

Psychrometers of this type might meet the interchangeability requirements, but would still suffer from low output for the temperature depressions being measured.

4.3 Thermistor - Thermocouple Hybrid Psychrometer

Another proposal initiated by the Forest Service was to use a thermocouple or thermopile to provide Peltier cooling to condense water on a measuring surface, then use the more sensitive thermistor for measuring wet bulb temperature.

This approach offers two advantages:

1. Thermistors measuring wet and dry bulb temperatures could be used in a bridge circuit, giving an accurate differential measurement;

2. One thermistor could be used for direct measurement of ambient temperature, eliminating the need for a thermocouple reference junction.

Considerations in analyzing this approach should include the effects of thermistor self-heating. The self-heating effect must be insignificant compared to the wet bulb temperature depression, yet still the thermistor must give the required output.

It was suggested that the cooling thermocouple be a bimetallic disc, with one material plated or vapor deposited onto the others.

The thermistor would then be epoxied to the disc with high thermal conductivity epoxy.

4.4 Diode Junction - Thermocouple Psychrometer

A diode junction psychrometer was considered to be basically similar to the thermistor/thermocouple hybrid, in that the thermocouple would be used to cool a surface to the dewpoint and the diode would indicate wet bulb temperature to a high degree of precision.

It was decided that both types would be analyzed simultaneously, with a distinction being made if the general approach appeared feasible.

4.5 Custom Chip Development

The U.S.D.A. Forest Service also initiated the concept of a custom chip which would consist of vapor deposited thermocouple junctions, signal amplifier, and reference junction.

It was pointed out that the chip would be a hybrid rather than a monolythic circuit because of the thermoelectric cooling requirement (metallic deposition) and the semiconductor circuitry. The concept of applying on board amplification to minimize noise in transmission appears to be the trend in transducer design, but the cost of developing the chip was questioned.

It was decided that the development cost would be investigated before proceeding with a detailed analysis.

4.6 Surface Thermal Conductivity

It was suggested that humidity be measured by measuring surface heat transfer from a central heater to the air sample. Since heat transfer

depends on temperature differential and heat transfer coefficient, the question to be answered is how surface heat transfer coefficient varies with air humidity in the 95-100% range. Heat transfer variation due to variation in ambient temperature would have to be taken into account or compensated out of the measurement.

4.7 Miniature Optical Dew Point Sensor

It was suggested that a dew point sensor be designed which utilized I.R. light emitting diodes for a source of I.R. reflected from a metallic mirror to a silicon detector. Dew point would be determined by cooling the mirror by means of a thermopile until fogging occurred and measuring dewpoint temperature by means of a thermistor.

The problem of long term contamination of the mirror surface was discussed, and it was concluded that this might be overcome by using a floating threshhold rather than a fixed reference, thus as the mirror became less reflective, the dew point would still be discernable. It was agreed that the sensor could not be immersed in ground water.

In terms of miniaturization, it was speculated that a sensor of approximately 2 inches in diameter by 6 inches in length could be designed. Outside support electronics would be required to produce cooling and to calculate potential based on dew point measurements.

5.0 Analysis of Alternative Sensor Designs

5.1 Multiple Junction Thermopile Psychrometer

5.1.1 Measurement Performance

The multiple junction thermopile psychrometer depicted in Figure 7 appears to be a viable choice for a sensitive soil psychrometer. Assuming

a thermopile of design similar to that shown in Figure 6, the following sensitivity can be expected:

$$S = \frac{Es}{T} = NK \qquad (5)$$

S = Sensitivity (microvolts/^{o}C)

Es = Signal voltage (microvolts)

T = Measured temperature (^{o}C)

N = Number of thermopile junction pairs

K = Thermoelectric constant
= 40 microvolts/^{o}C for chromel - constantan)

Assuming a 72 junction pair thermopile, and chromel - constantan a sensitivity of 2.88 millivolts per ^{o}C could be expected. Reference to Table II-b shows that at 20 ^{o}C, wet bulb depression is about .025 ^{o}C/bar. This transfers into an output of 72 microvolts/bar which is considerably higher (72 times) than dual junction devices. Reference (48) points out that most thin film thermoelectric materials with film thickness greater than 100 x 10^{-6} mm demonstrate the same thermoelectric constant as does the bulk material.

The range of this device would be the same as that for dual junction psychrometers, thus -.1 to -60 bars should be no problem. Since the thermopile psychrometer measures wet bulb depression, its output will vary with ambient temperature. It would be difficult to fabricate a thermopile with a terminal extension such that one leg of the thermopile could be used to measure ambient temperature. Thus a separate, ambient temperature measuring thermocouple would be required. Use

of a thermocouple for ambient temperature measurement would further require a reference junction compensator, most likely positioned in the readout device.

5.1.2 Reliability

Thin film thermopiles are placed on or between mylar film, and can be bent, folded and reportedly dipped in boiling water as liquid nitrogen while operating (49). Total thermopile thickness would be on the order of .05 mm.

5.1.3 Limitations in Application and Potential Problems

Several potential problems exist and would have to be solved during a development program. First, each wet junction must be electrically isolated from the other junctions. If the thermopile wet junctions are left uncovered or uncoated, a possibility of shorting between junctions due to water droplet condensation exists. Theoretically, the water is pure, thus non-conducting, but practically, it may have a low resistance. It is possible that very tiny droplets will form on each of the cold junctions, not overlapping, but if so, they will also evaporate very quickly, making the reading of wet bulb depression very difficult.

The alternative to leaving wet junctions bare is to coat them with a very thin layer of mylar or parylene. This will reduce sensitivity somewhat. The proper fabrication procedure should be experimentally refined to yield optimum performance results.

One essential feature of the psycrometers is that they be interchangeable without loss of accuracy, or the need for individual calibration curves. The fabrication process involves deposition of the thermoelectric materials through two masks. Generally speaking, the deposited

film thickness can be controlled precisely, thus the thermopiles should exhibit interchangeable performance. If not, it may be necessary to test and select thermopiles with performance within the acceptable range.

5.1.4 Size

The thermopile can be fabricated to almost any size. The junction patterns are photo-reduced, thereby assuring continuity without shorting the very small sizes. The thermopile shown in Figure 6 is approximately 1 inch in diameter at the outer junction circumference.

Considering the need to fabricate spacers, run leads, etc., a sensor diameter of 0.5 inches appears practical. Sensor length would be approximately 1.5 inches. Four leads would come off of the sensor (three could be possible) - two for the thermopile and two for the ambient temperature thermocouple.

5.1.5 Cost

The largest cost factor here would be in the development of the initial thermopile. Several companies involved in plated heating elements and printed circuits were contacted. Given a full size drawing of the thermopile pattern, prototype masks could be fabricated and a sample run of approximately 20 units of a single thickness made for approximately $20,000. Multiple or gang masks might be used in large scale production, but would not be attempted until the pattern design was finalized.

The production price of the thermopiles was very roughly estimated at $15 - 25 each if market volume was in the tens of thousands of units per year.

The cost of detailed sensor design, development and testing was estimated at $60,000 by Novatek, Inc. assuming that only one iteration of thermopile design and fabrication was required.

The production cost of the additional sensor parts, less readout device, was estimated by Novatek to be $10 per sensor. Cost to manufacture the outer sensor would thus be $25 - 35, and the market price could then be expected to be approximately $50.

Readout equipment would not differ greatly from that used with dual junction psychrometers, thus would retail for approximately $1,000 per unit.

5.2 Thermocouple - Thermistor Hybrid

5.2.1 Measurement Performance

Assume a sensor circuit as shown in Figure 8. A typical thermistor (Omega UUA 35J3) exhibits the following resistance characteristic:

T(^{o}C)	R(ohms)
0	16,325
25	5000.0
65	1041.5

The concern is to minimize thermistor self-heating, such that the wet bulb thermistor, Twb, does not self heat, thereby creating an error. If self heating of less than 0.001 ^{o}C is desired, then the thermistor must dissipate less than .001 milliwatts (dissipation constant = 1.0 milliwatt/^{o}C). For the bridge of Figure 8, the maximum self heating for a given supply voltage, Es, will be:

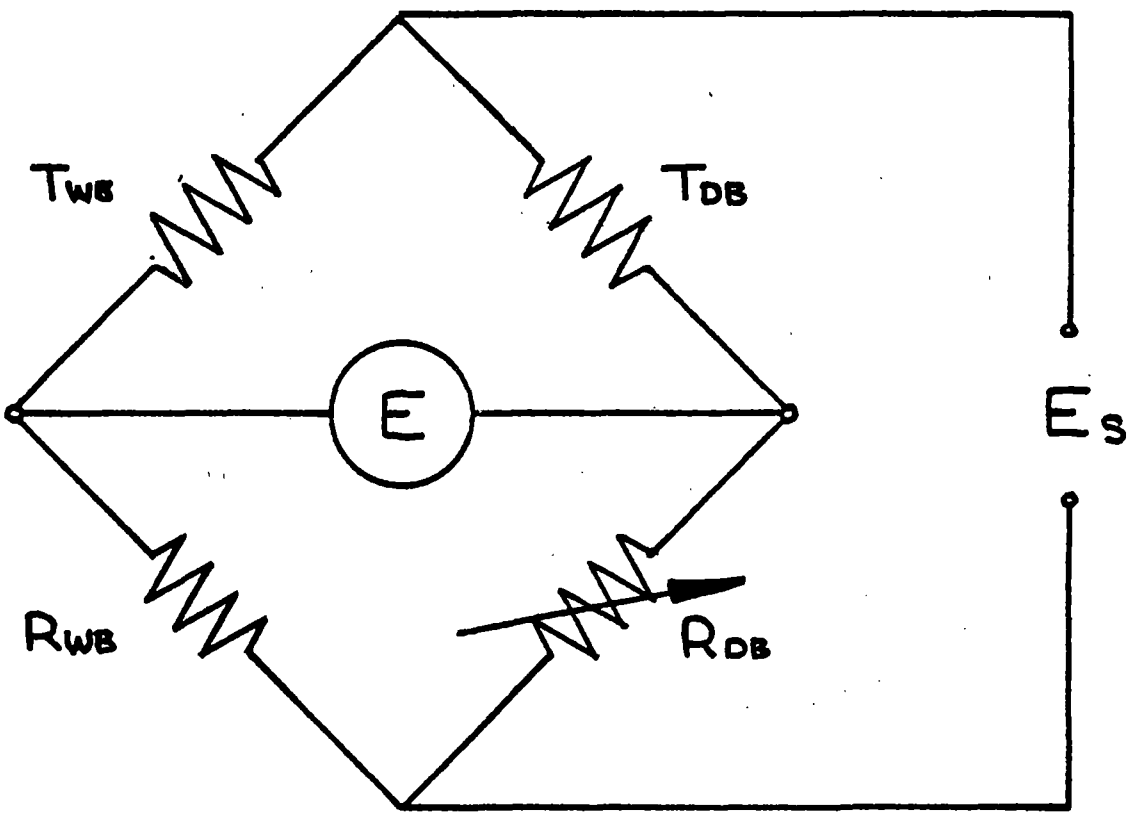


Figure 8

Typical Thermistor Bridge

E_s = Supply Voltage

E = Measured Voltage

T_{wb} = Wet Bulb Thermistor (Variable Resistance)

T_{db} = Dry Bulb Thermistor (Variable Resistance)

R_{wb} = Wet Bulb Resistance (Fixed) = 20,000 ohms

R_{db} = Dry Bulb Resistor (Adjustable)

scale factor (mv/bar) is very sensitive to ambient temperature. If the scale factor itself could be linearized by temperature compensation to better than 8%, the required accuracy of .25 bar at -15 bar and .5 bar at -60 bar could be achieved.

Figure 9 shows a conceptual drawing of a hybrid thermocouple/ thermistor sensor. The lower (wet bulb) thermistor is in intimate thermal contact with a thin copper plate onto which a negative thermoelectric metal (say constantan) has been plated. Water is condensed on the plate by energizing the junction (current and time determined experimentally), which serves as the wet bulb. Low thermal mass allows the wet junction thermistor to measure Twb with maximum sensitivity.

If the thermistor bridge output is compensated, ambient temperature measurements need not be made. This represents the ideal situation of having a single output which indicates soil moisture potential over the entire range, -.1 to -60 bars, and 0 to 65^{o}C.

5.2.2 Reliability

Thermistors may be glass encapsulated for maximum environmental protection, therefore are very rugged devices.

5.2.3 Limitations in Application - Potential Problems

The use of a bimetal plate for the wet junction has not been proven, but appears to be a viable approach. Copper can easily be electroplated onto a constantan substrate without an elaborate or expensive set up.

5.2.4 Size

Commercially available thermistors of 0.1 inch diameter are commonplace. The sensor of Figure 9 is approximately 0.3 inches in diameter and 1.0 inches long.

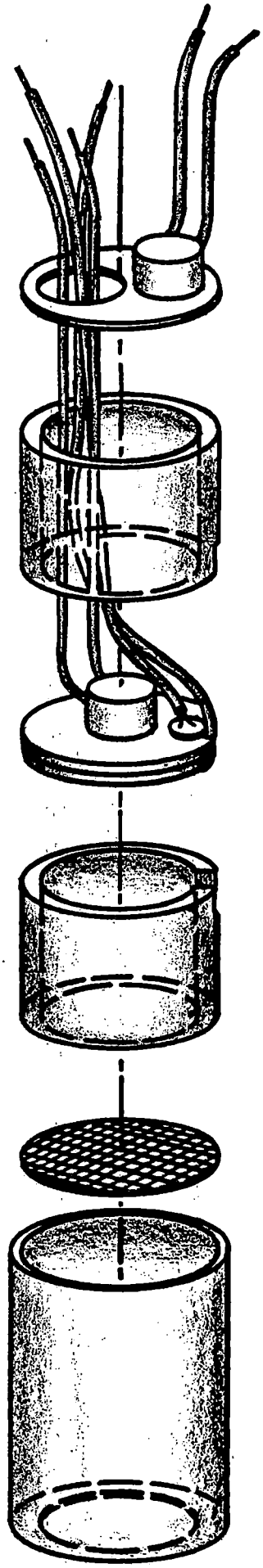


Figure 9

Thermistor/Thermocouple
Psychrometer

5.2.5 Cost

Thermistors with 0.2% interchangeability are available for less than $10 in quantity. Presumably the thermoelectric wet bulb would be manufactured by electroplating and in quantity should be less than $5 each.

Additional sensor parts were estimated by Novatek, Inc. to be $10 per set. The basic cost per sensor, excluding assembly and test would be approximately $35, and the market price would be on the order of $75 per sensor.

Readout electronics would require a cooling current source, bridge power supply, and high impedance millivolt meter. Cost of readout devices in production would be similar to dual junction psychrometer source at approximately $1,000.

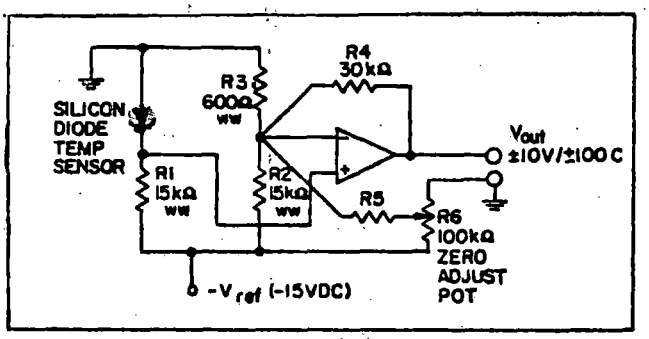
Development of the sensor would require little expensive risk since standard components would be used. Novatek, Inc. estimates the sensor design, conpensations circuit design, and readout electronics design, development and test at $30,000.

5.3 Diode Junction - Thermopile Hybrid Psychrometer

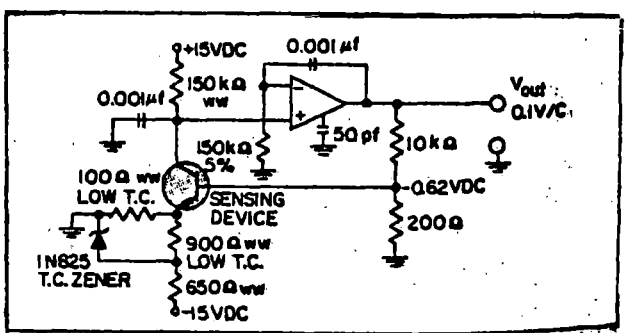
5.3.1 Measurement Performance

Diode and transistor sensors offer an advantage over thermistors in that they can be linearized much more easily, over a wide (0-150 ^{o}C) temperature range. Reference (39) shows diode and transistor sensor circuitry which have outputs as high as 100 mv/^{o}C. Five such circuits are reproduced as Figure 10.

Diodes or transistors would be used identically to thermistors shown in Figure 9. The wet bulb junction would be a plated thermocouple, energized by a current from the readout electronics. Because output



LINEAR THERMOMETER based on silicon diode sensor.

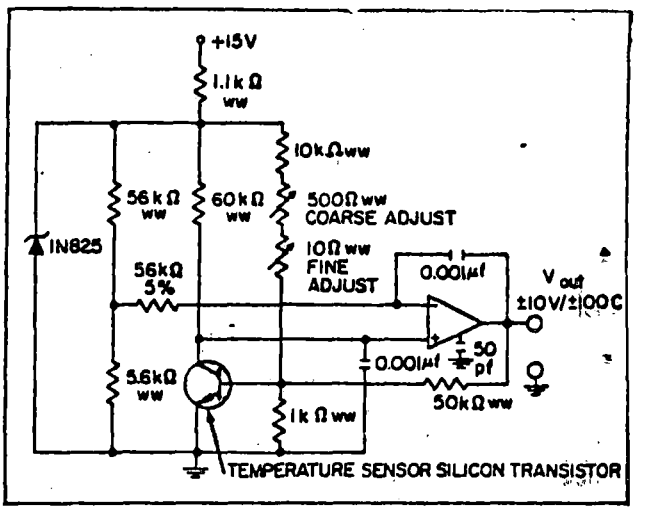


HIGH-RESOLUTION linear thermometer, with transistor sensor.

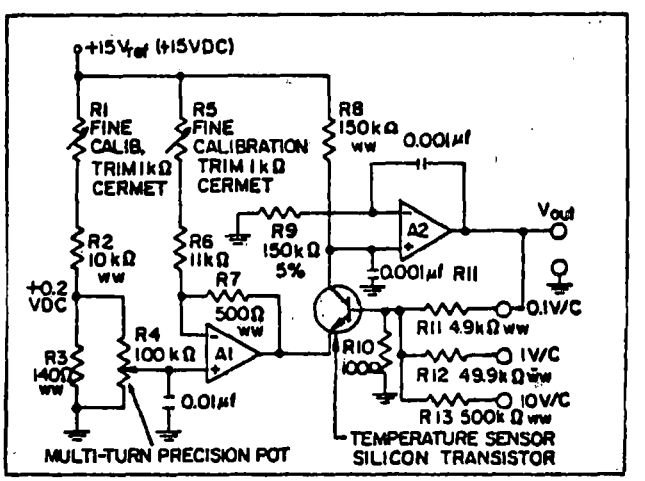
From: Instruments and Control Systems, June, 1972

Figure 10

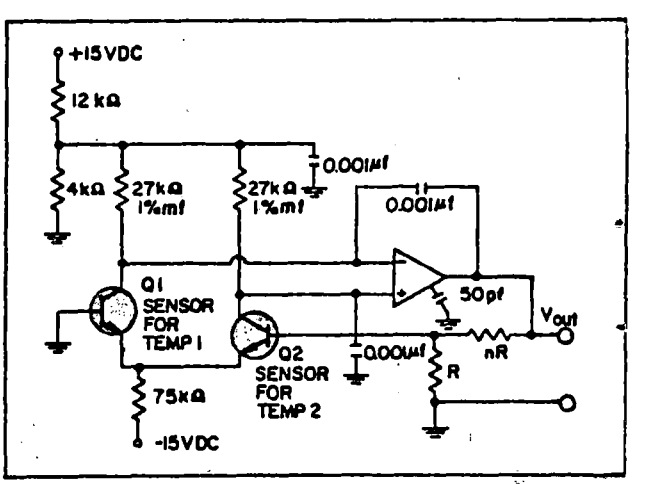
Linear Thermometer Circuits Used With Diode Junction And Transistor Temperature Sensors



FULLY REGULATED linear thermometer.



PRECISION linear thermometer with programmable offset.



PRECISION differential thermometer.

scale factor would remain constant over the entire measurement range, 0-65 ^{o}C, a moisture potential sensitivity could be expected as follows:

Tamb	Sensitivity
0^{o}C	.77 millivolts/bar
20^{o}C	2.76 millivolts/bar
50^{o}C	13.37 millivolts/bar

Note that the improvement in linearity does not overcome the fact that the temperature depression representing 1 bar water potential increases with ambient temperature. The relatively large millivolt outputs could, however, be easily and cleanly amplified and used as input to a microprocessor network which would correct and display moisture potential independently of ambient temperature.

5.3.2 Reliability

The diode junction sensor would be as reliable as the thermistor sensor, and should not degrade with time.

5.3.3 Limitation to Application - Potential Problems

The diode junction sensor would exhibit similar problems to those discussed for thermistor sensors. Diodes and transistors, while cheaper and more widely available from thermistors may not, however, be matched in characteristics as closely as thermistors. This would be an important consideration since the sensor design shown would contain only the diode or transistor. Linearizing circuitry would be left to the associated readout electronics.

One approach which avoids this problem would be to provide the circuitry (discrete components) in a package integral with, or nearby,

the sensor itself. The circuitry could be trimmed to very close tolerance scale factor, which would insure the interchangeability of sensors.

5.3.4 Size

Figure 9 could well represent the diode junction sensor, but in order to use standard components, the sensor diameter would be 0.75 inches. Length would be approximately 3 inches.

Integral circuitry would add a package of approximate dimenstions, 1 inch by 2 inches by 3 inches.

5.3.5 Cost

The basic sensor cost, estimated by Novatek, Inc., would be $12 assembled. Selling price would be $25. This does not include the linearizing circuit which would add approximately $25 to the selling price.

Readout electronics would sell for approximately $1,000 with electronics, including cooling current supply in the package. The readout device could be reduced in price to approximately $700, if electronics were integral with sensor.

5.4 Custom Chip Psychrometer

Film Microelectronics, Inc. of Burlington, Mass. was consulted concerning the details of custom chip development. It was difficult to obtain an accurate quotation without supplying a discrete component circuit diagram but Novatek, Inc. was informed that the minimum cost to develop a custom chip was $100,000. It was suggested the standard integrated circuits already developed be investigated and used as building blocks for the described sensor.

As a result, the Analog Devices, two terminal IC temperature transducer was investigated. Appendix A contains the specification sheet on the device and it was considered to be a viable candidate for psychrometer temperature instrumentation. The devices are trimmed to provide an output of 1 microamp/^{o}C.

Differential temperature measurements using a circuit as shown in Figure 12 of Appendix A can be made with output of 10 mv/^{o}C. In terms of moisture potential sensitivity, the outputs are:

Tamb	Sensitivity
0^{o}C	.077 mv/bar
20^{o}C	.276 mv/bar
50^{o}C	1.337 mv/bar

The standard package IC would be used as the thermistor in Figure 9. The overall sensor size would be .75 inches in diameter by 1.5 inches in length. The "flat pack" configuration would allow a sensor size of .4 inches in diameter by 1 inch long.

As with the semiconductor sensors, a thermoelectric cooling junction would be required. The IC cap is nickel, so it may be possible to plate a layer of copper directly to it, thereby creating an integral sensor/cooling element.

6.0 Recommendations

Table III summarizes sensor characteristics for six alternative designs and one commercially available dual junction psychrometer. The alternatives summarized in Table III are identified as:

No.	Alternative
1.	Commercially available dual junction thermocouple psychrometer.
2.	Discrete junction thermopile psychrometer (Figure 5).
3.	Plated thermopile psychrometer (Figure 7).
4.	Thermistor/thermocouple hybrid psychrometer (Figure 8).
5.	Diode junction/thermocouple psychrometer.
6.	Custom chip, dual junction psychrometer.
7.	IC sensor/thermocouple psychrometer.

Based on the options analyzed and the apparent task of developing each sensor the following preliminary experimental work should be carried out:

1. Fabricate a bread board discrete junction thermopile sensor and test the thermopile concept in calibrated atmospheres. Of particular concern would be the ability to consistently wet the central junctions.

2. Experiment with a condensing thermocouple fabricated by laboratory electroplating of copper on .010 inch

TABLE III

SUMMARY OF SENSOR CHARACTERISTICS

sor	1	2	3	4	5	6	7
ver Requirements (Cooling)	.3 μW	22 μW	90 μW	~ /μW	~ /μW	.3μW	~ /uW
put Sensitivity 0°C 0°C (μv/bar) 0°C	.13 .47 2.28	20 72 349	20 72 349	120 2800 85800	770 2760 13370	By design	77 276 1337
ıge	0 to -60	0 to -60	0 to -60	0 to -60	0 to -60	0 to -60	0 to -60
iability	Good	Poor - Good	Good	Excellent	Excellent	Good - Exc.	Excellent
uracy w/o cal. @ -15 bar @ -60 bar	.75 bar 3 bar	1 bar 4 bar	.5 bar 1.0 bar	.25 bar 1.0 bar	.5 bar 1.0 bar	?	.25 bar .5 bar
:	0.3" dia. X 1.5"	1.0" dia. X 3.0"	.5" dia. X 1.5"	3" dia. X 1.0"	.75" dia. X 3.0"	1" X 2" X 3"	0.4" dia. X 1.0"
bable Price Sensor Readout	$ 12 $1,000	$ 65 $ 1,000	$ 50 $ 1,000	$ 75 $ 1,000	$25 or $50 $1,000 $700	est. $ 25 $ 500	$ 25 $ 500
elopment Cost	None	$20,000	$60,000	$30,000	$ 30,000	$130,000	$30,000

constantan sheet. This component is a critical part of the thermistor and semiconductor psychrometers.

3. Electroplate a layer of copper on the Analog Devices AD590 IC temperature transducer and determine whether or not a consistent wet bulb could be created and measured.

NOVATEK, INC. has ordered the hardware necessary to perform the above preliminary investigations, but was not able to complete testing during the extent of the current project. Results will be in a later report.

The psychrometer concept using the Analog Devices IC sensor appears to be the most attractive alternative for a low cost, accurate, interchangeable sensor.

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Thermocouple Psychrometry

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ANALOG DEVICES

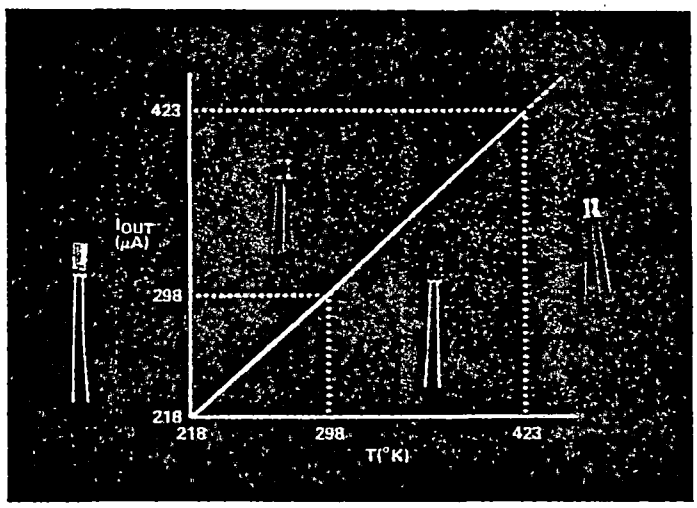
Two-Terminal IC Temperature Transducer

AD590

PRELIMINARY TECHNICAL DATA

FEATURES

Linear Current Output: 1μA/°K
Wide Range: -55°C to +150°C
Probe Compatible Ceramic Sensor Package
Two-Terminal Device: Voltage In/Current Out
Laser Trimmed to ±0.5°C Calibration Accuracy (AD590M)
Excellent Linearity: ±0.3°C Over Full Range (AD590M)
Wide Power Supply Range: +4V to +30V
Sensor Isolation from Case
Low Cost: $1.95 (100's, AD590IH)



PRODUCT DESCRIPTION

The AD590 is a two-terminal integrated circuit temperature transducer which produces an output current proportional to absolute temperature. For supply voltages between +4V and +30V the device acts as a high impedance, constant current regulator passing 1μA/°K. Laser trimming of the chip's thin film resistors is used to calibrate the device to 298.2μA output at 298.2°K (+25°C).

The AD590 should be used in any temperature sensing application below +150°C in which conventional electrical temperature sensors are currently employed. The inherent low cost of a monolithic integrated circuit combined with the elimination of support circuitry makes the AD590 an attractive alternative for many temperature measurement situations. Linearization circuitry, precision voltage amplifiers, resistance measuring circuitry and cold junction compensation are not needed in applying the AD590.

In addition to temperature measurement, applications include temperature compensation or correction of discrete components, biasing proportional to absolute temperature, flow rate measurement, level detection of fluids and anemometry. The AD590 is available in chip form making it suitable for hybrid circuits and fast temperature measurements in protected environments.

The AD590 is particularly useful in remote sensing applications. The device is insensitive to voltage drops over long lines due to its high impedance current output. Any well-insulated twisted pair is sufficient for operation hundreds of feet from the receiving circuitry. The output characteristics also make the AD590 easy to multiplex: the current can be switched by a CMOS multiplexer or the supply voltage can be switched by a logic gate output.

PRODUCT HIGHLIGHTS

1. The AD590 is a calibrated two terminal temperature sensor requiring only a dc voltage supply (+4V to +30V). Costly transmitters, filters, lead wire compensation and linearization circuits are all unnecessary in applying the device.
2. State-of-the-art laser trimming at the wafer level in conjunction with extensive final testing insures that AD590 units are easily interchangeable.
3. Superior interference rejection results from the output being a current rather than a voltage. In addition, power requirements are low (1.5mW's @ 5V @ +25°C). These features make the AD590 easy to apply as a remote sensor.
4. The high output impedance (>10MΩ) provides excellent rejection of supply voltage drift and ripple. For instance, changing the power supply from 5V to 10V results in only a 1μA maximum current change, or 1°C equivalent error.
5. The AD590 is electrically durable: it will withstand a forward voltage up to 44V and a reverse voltage of 20V. Hence, supply irregularities or pin reversal will not damage the device.
6. The device is hermetically sealed in both a ceramic sensor package and in to TO-52 package. MIL-STD-883 processing to level B is available and, for large unit volumes, special accuracy requirements over limited temperature ranges can be satisfied by selections at final test. The device is also available in chip form.

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Route 1 Industrial Park; P.O. Box 280; Norwood, Mass. 02062
Tel: 617/329-4700 TWX: 710/394-6577
West Coast 714/842-1717 Mid-West 312/894-3300 Texas 214/231-5094

SPECIFICATIONS (typical @ +25°C and V_S = 5V unless otherwise noted)

MODEL	AD590I	AD590J	AD590K	AD590L	AD590M
ABSOLUTE MAXIMUM RATINGS					
Forward Voltage (E+ to E–)	+44V	•	•	•	•
Reverse Voltage (E+ to E–)	–20V	•	•	•	•
Breakdown Voltage (Case to E+ or E–)	±200V	•	•	•	•
Rated Performance Temperature Range[1]	–55°C to +150°C	•	•	•	•
Storage Temperature Range[1]	–65°C to +155°C	•	•	•	•
Lead Temperature (Soldering, 10 sec)	+300°C	•	•	•	•
POWER SUPPLY					
Operating Voltage Range	+4V to +30V	•	•	•	•
OUTPUT					
Nominal Current Output @ +25°C (298.2°K)	298.2μA	•	•	•	•
Nominal Temperature Coefficient	1μA/°K	•	•	•	•
Calibration Error @ +25°C	±10.0°C max	±5.0°C max	±2.5°C max	±1.0°C max	±0.5°C max
Absolute Error[2] (over rated performance temperature range)					
Without External Calibration Adjustment	±20.0°C max	±10.0°C max	±5.5°C max	±3.0°C max	±1.7°C max
With +25°C Calibration Error Set to Zero	±5.8°C max	±3.0°C max	±2.0°C max	±1.6°C max	±1.0°C max
Nonlinearity	±3.0°C max	±1.5°C max	±0.8°C max	±0.4°C max	±0.3°C max
Repeatability[3]	±0.1°C max	•	•	•	•
Long Term Drift[4]	±0.1°C month max	•	•	•	•
Current Noise	40pA$\sqrt{\text{Hz}}$	•	•	•	•
Power Supply Rejection					
+4V ≤ V_S ≤ +5V	0.5μA/V	•	•	•	•
+5V ≤ V_S ≤ +15V	0.2μA/V	•	•	•	•
+15V ≤ V_S ≤ +30V	0.1μA/V	•	•	•	•
Case Isolation to Either Lead	$10^{10}\Omega$	•	•	•	•
Effective Shunt Capacitance	100pF	•	•	•	•
Electrical Turn-On Time[5]	20μs	•	•	•	•
Reverse Bias Leakage Current[6] (Reverse Voltage = 10V)	10pA	•	•	•	•
PRICE[7]					
H Package					
(1–24)	$3.25	$3.90	$ 7.80	$15.60	$36.70
(25–99)	$2.50	$3.00	$ 6.20	$12.40	$27.95
(100–999)	$1.95	$2.30	$ 4.65	$ 9.40	$22.25
F Package					
(1–24)	$6.50	$9.75	$11.70	$19.50	$43.50
(25–99)	$5.25	$6.80	$ 9.30	$16.10	$35.10
(100–999)	$4.15	$5.85	$ 7.00	$12.90	$26.65
PRICE–PROCESSED TO MIL-STD-883B					
H Package					
(1–24)	–	$ 9.75	$14.25	$23.40	$46.25
(25–99)	–	$ 7.95	$10.55	$18.60	$37.05
(100–999)	–	$ 8.85	$ 8.15	$13.60	$28.45
F Package					
(1–24)	–	$12.35	$19.50	$28.60	$54.50
(25–99)	–	$10.25	$16.10	$22.95	$44.20
(100–999)	–	$ 8.20	$11.75	$17.65	$34.10

*Specifications same as AD590I

[1] The AD590 has been used at –100°C and +200°C for short periods of measurement with no physical damage to the device. However, the absolute errors specified apply to only the rated performance temperature range.

[2] See page 4 for explanation of error components. Note that ±1°C error is the equivalent of ±1μA error.

[3] Maximum deviation between +25°C readings after temperature cycling between –55°C and +150°C; guaranteed not tested.

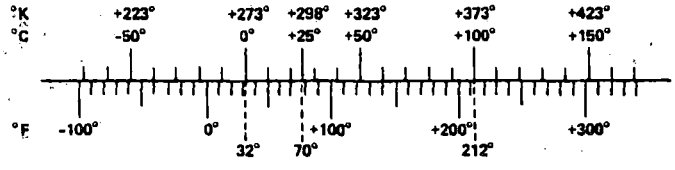
[4] Conditions: constant +5V, constant +125°C; guaranteed, not tested.

[5] Does not include self heating effects; see page 5 for explanation of these effects.

[6] Leakage current doubles every 10°C.

[7] Chips are available to J specifications; minimum order is 25 chips; 25–99 price: $2.00/chip; 100–999 price: $1.40/chip; consult local sales office for large volume pricing; consult Chip Catalog for applications detail.

Specifications subject to change without notice.



TEMPERATURE SCALE CONVERSION EQUATIONS

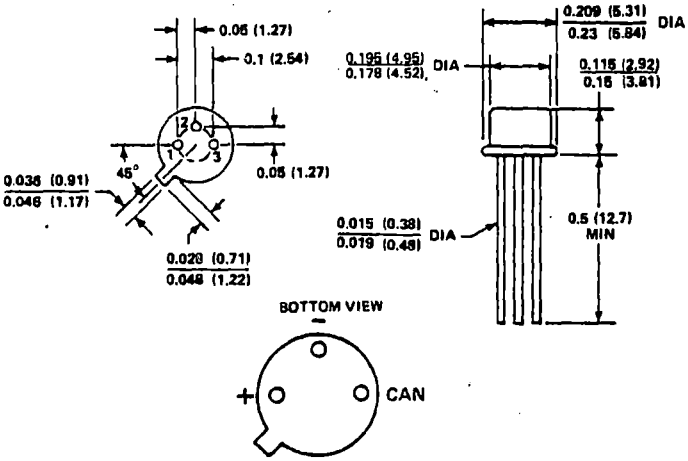
$$°C = \frac{5}{9}(°F - 32) \qquad °K = °C + 273.15$$

$$°F = \frac{9}{5}°C + 32 \qquad °R = °F + 459.7$$

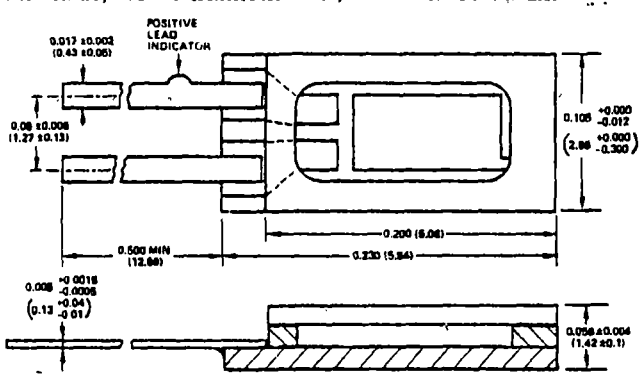
OUTLINE DIMENSIONS AND PIN DESIGNATIONS

Dimensions shown in inches and (mm).

TO-52 PACKAGE: DESIGNATION "H"

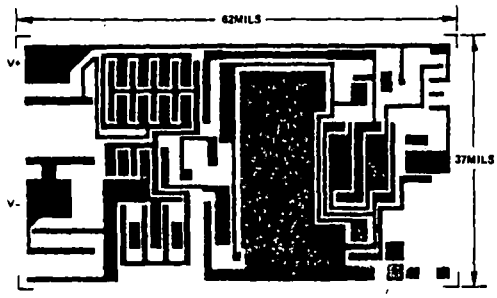


The 590H has 60μ inches of gold plating on its Kovar leads and Kovar header. A resistance welder is used to seal the nickel cap to the header. The AD590 chip is eutectically mounted to the header and ultrasonically bonded to with 1 mil aluminum wire. Kovar composition: 53% iron nominal; 29% ±1% nickel; 17% ±1% cobalt; 0.65% manganese max; 0.20% silicon max; 0.10% aluminum max; 0.10% magnesium max; 0.10% zirconium max; 0.10% titanium max; 0.06% carbon max.



FLAT-PACK PACKAGE: DESIGNATION "F"

The 590F is a ceramic package with gold plating on its Kovar leads, Kovar lid, and chip cavity. Solder of 80/20 Au/Sn composition is used for the 1.5 mil thick solder ring under the lid. The chip cavity has a nickel underlay between the metalization and the gold plating. The AD590 chip is eutectically mounted in the chip cavity at 400°C and ultrasonically bonded to with 1 mil aluminum wire. Note that the chip is in direct contact with the ceramic base, not the metal lid.



Metalization Diagram

CIRCUIT DESCRIPTION[1]

The AD590 uses a fundamental property of the silicon transistors from which it is made to realize its temperature proportional characteristic: if two identical transistors are operated at a constant ratio of collector current densities, r, then the difference in their base-emitter voltages will be (kT/q)(ln r). Since both k, Boltzman's constant and q, the charge of an electron, are constant, the resulting voltage is directly proportional to absolute temperature (PTAT).

In the AD590, this PTAT voltage is converted to a PTAT current by low temperature coefficient thin film resistors. The total current of the device is then forced to be a multiple of this PTAT current. Referring to Figure 1, the schematic diagram of the AD590, Q8 and Q11 are the transistors that produce the PTAT voltage. R5 and R6 convert the voltage to current. Q10, whose collector current tracks the collector currents in Q9 and Q11, supplies all the bias and substrate leakage current for the rest of the circuit, forcing the total current to be PTAT. R5 and R6 are laser trimmed on the wafer to calibrate the device at +25°C.

Figure 2 shows the typical V–I characteristic of the circuit at +25°C and the temperature extremes.

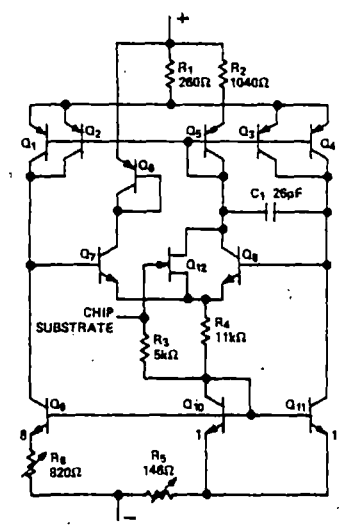


Figure 1. Schematic Diagram

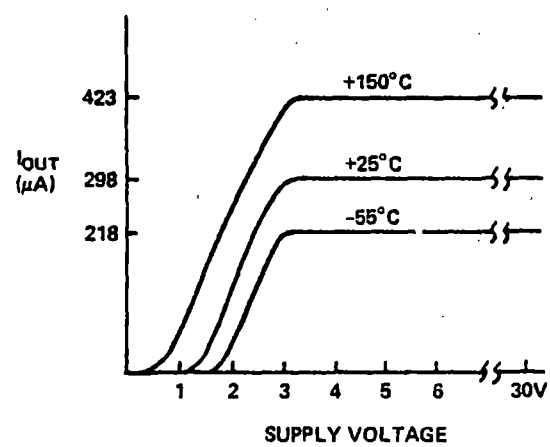


Figure 2. V–I Plot

[1] For a more detailed circuit description see M.P. Timko, "A Two-Terminal IC Temperature Transducer," IEEE J. Solid State Circuits, Vol. SC-11, p. 784-788, Dec. 1976.

EXPLANATION OF TEMPERATURE SENSOR SPECIFICATIONS

The way in which the AD590 is specified makes it easy to apply in a wide variety of different applications. It is important to understand the meaning of the various specifications and the effects of supply voltage and thermal environment on accuracy.

The AD590 is basically a PTAT (proportional to absolute temperature)[1] current regulator. That is, the output current is equal to a scale factor times the temperature of the sensor in degrees Kelvin. This scale factor is trimmed to 1μA/°K at the factory, by adjusting the indicated temperature (i.e. the output current) to agree with the actual temperature. This is done with 5V across the device at a temperature within a few degrees of 25°C (298.2°K). The device is then packaged and tested for accuracy over temperature.

CALIBRATION ERROR

At final factory test the difference between the indicated temperature and the actual temperature is called the calibration error. Since this is a scale factor error, its contribution to the total error of the device is PTAT. For example, the effect of the 1°C specified maximum error of the AD590L varies from 0.73°C at -55°C to 1.42°C at 150°C. Figure 3 shows how an exaggerated calibration error would vary from the ideal over temperature.

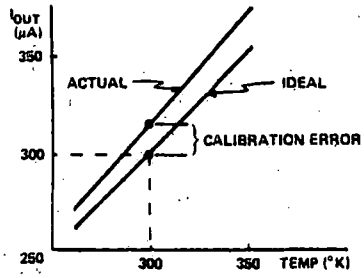


Figure 3. Calibration Error vs. Temperature

The calibration error is a primary contributor to maximum total error in all AD590 grades. However, since it is a scale factor error, it is particularly easy to trim. Figure 4 shows the most elementary way of accomplishing this. To trim this circuit the temperature of the AD590 is measured by a reference temperature sensor and R is trimmed so that V_T = 1mV/°K at that temperature. Note that when this error is trimmed out at one temperature, its effect is zero over the entire temperature range. In most applications there is a current to voltage conversion resistor (or, as with a current input ADC, a reference) that can be trimmed for scale factor adjustment.

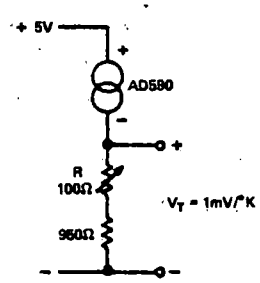


Figure 4. One Temperature Trim

[1] T(°C) = T(°K) - 273.2; Zero on the Kelvin scale is "absolute zero";

ERROR VERSUS TEMPERATURE: WITH CALIBRATION ERROR TRIMMED OUT

Each AD590 is also tested for error over the temperature range with the calibration error trimmed out. This specification could also be called the "variance from PTAT" since it is the maximum difference between the actual current over temperature and a PTAT multiplication of the actual current at 25°C. This error consists of a slope error and some curvature, mostly at the temperature extremes. Figure 5 shows a typical AD590K temperature curve before and after calibration error trimming.

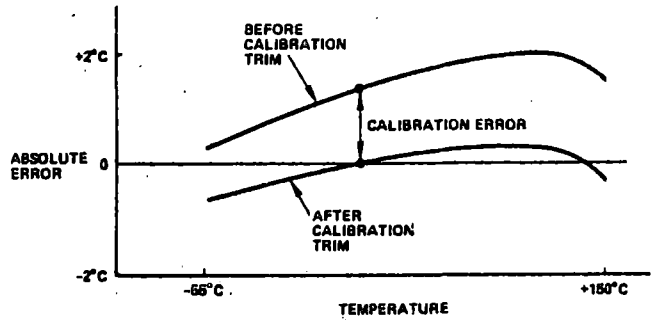


Figure 5. Effect of Scale Factor Trim on Accuracy

ERROR VERSUS TEMPERATURE: NO USER TRIMS

Using the AD590 by simply measuring the current, the total error is the "variance from PTAT" described above plus the effect of the calibration error over temperature. For example the AD590L maximum total error varies from 2.33°C at -55°C to 3.02°C at 150°C. For simplicity, only the larger figure is shown on the specification page.

NONLINEARITY

Nonlinearity as it applies to the AD590 is the maximum deviation of current over temperature from a best-fit straight line. The nonlinearity of the AD590 over the -55°C to +150°C range is superior to all conventional electrical temperature sensors such as thermocouples, RTD's and thermistors. Figure 6 shows the nonlinearity of the typical AD590K from Figure 5.

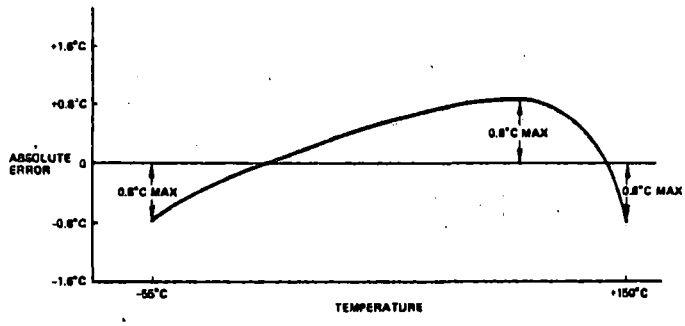


Figure 6. Nonlinearity

Figure 7A shows a circuit in which the nonlinearity is the major contributor to error over temperature. The circuit is trimmed by adjusting R_1 for a 0V output with the AD590 at 0°C. R_2 is then adjusted for 10V out with the sensor at 100°C. Other pairs of temperatures may be used with this procedure as long as they are measured accurately by a reference sensor. Note that for +15V output (150°C) the V+ of the op amp must be greater than 17V. Also note that V- should be at least -4V: if V- is ground there is no voltage applied across

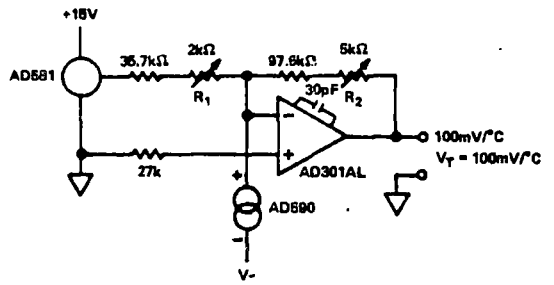


Figure 7A. Two Temperature Trim

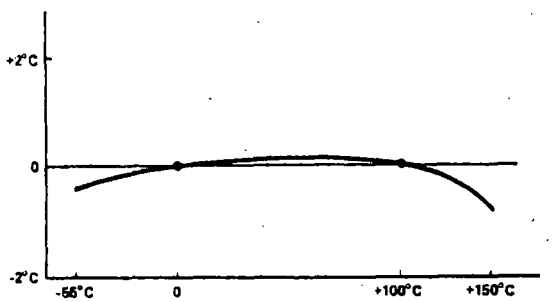


Figure 7B. Typical Two-Trim Accuracy

VOLTAGE AND THERMAL ENVIRONMENT EFFECTS

The power supply rejection specifications given on page 2 show the maximum expected change in output current versus input voltage changes. The insensitivity of the output to input voltage allows the use of unregulated supplies. It also means that hundreds of ohms of resistance (such as a CMOS multiplexer) can be tolerated in series with the device.

It is important to note that using a supply voltage other than 5V does not change the PTAT nature of the AD590. In other words, this change is equivalent to a calibration error and can be removed by the scale factor trim (see page 4).

The AD590 specifications are guaranteed for use in a low thermal resistance environment with 5V across the sensor. Large changes in the thermal resistance of the sensor's environment will change the amount of self-heating and result in changes in the output which are predictable but not necessarily desirable.

The thermal environment in which the AD590 is used determines two important characteristics: the effect of self heating and the response of the sensor with time.

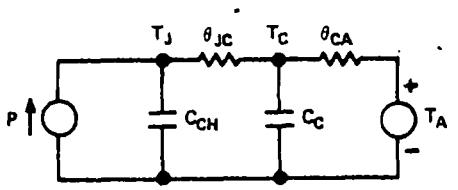


Figure 8. Thermal Circuit Model

Figure 8 is a model of the AD590 which demonstrates these characteristics. As an example, for the TO-52 package, θ_{JC} is the thermal resistance between the chip and the case, about 26°C/watt. θ_{CA} is the thermal resistance between the case and its surroundings and is determined by the characteristics of the thermal connection. Power source P represents the power dissipated on the chip. The rise of the junction temperature, T_J, above the ambient temperature T_A is:

$$T_J - T_A = P(\theta_{JC} + \theta_{CA}). \qquad \text{Eq. 1}$$

Table 1 gives the sum of θ_{JC} and θ_{CA} for several common thermal media for both the "H" and "F" packages. The heatsink used was a common clip-on. Using Equation 1, the temperature rise of an AD590 "H" package in a stirred bath at +25°C, when driven with a 5V supply, will be 0.06°C. However, for the same conditions in still air the temperature rise is 0.72°C. For a given supply voltage, the temperature rise varies with the current and is PTAT. Therefore, if an application circuit is trimmed with the sensor in the same thermal environment in which it will be used, the scale factor trim compensates for this effect over the entire temperature range.

MEDIUM	$\theta_{JC}+\theta_{CA}$(°C/watt)		τ (sec)(Note 3)	
	H	F	H	F
Aluminum Block	30	10	0.6	0.1
Stirred Oil[1]	42	60	1.4	0.6
Moving Air[2]				
With Heat Sink	45	—	5.0	—
Without Heat Sink	115	190	13.5	10.0
Still Air				
With Heat Sink	191	—	108	—
Without Heat Sink	480	650	60	30

[1] Note: τ is dependent upon velocity of oil; average of several velocities listed above.

[2] Air velocity ≅ 9ft/sec.

[3] The time constant is defined as the time required to reach 63.2% of an instantaneous temperature change.

Table 1. Thermal Resistances

The time response of the AD590 to a step change in temperature is determined by the thermal resistances and the thermal capacities of the chip, C_{CH}, and the case, C_C. C_{CH} is about 0.04 watt-sec/°C for the AD590. C_C varies with the measured medium since it includes anything that is in direct thermal contact with the case. In most cases, the single time constant exponential curve of Figure 9 is sufficient to describe the time response, T (t). Table 1 shows the effective time constant, τ, for several media.

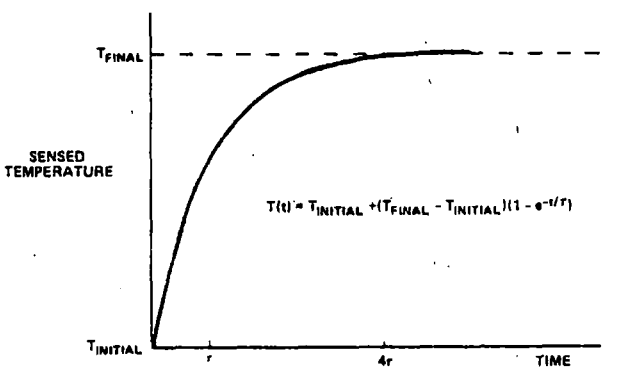


Figure 9. Time Response Curve

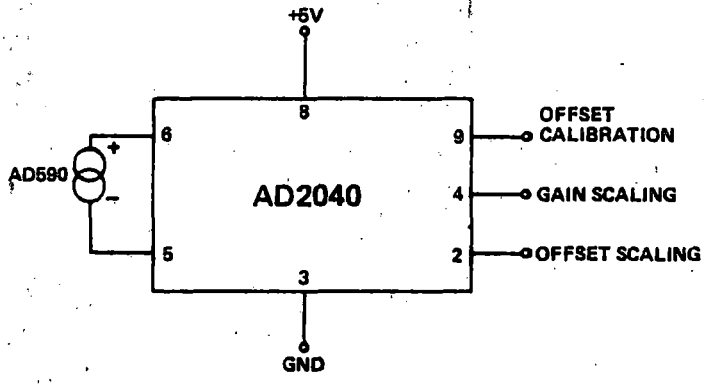


Figure 10. Variable Scale Display

Figure 10 demonstrates the use of a low-cost Digital Panel Meter for the display of temperature on either the Kelvin, Celsius or Fahrenheit scales. For Kelvin temperature Pins 9, 4 and 2 are grounded; and for Fahrenheit temperature Pins 4 and 2 are left open.

The above configuration yields a 3 digit display with 1°C or 1°F resolution, in addition to an absolute accuracy of ±2.0°C over the -55°C to +125°C temperature range if a one-temperature calibration is performed on an AD590K, L, or M.

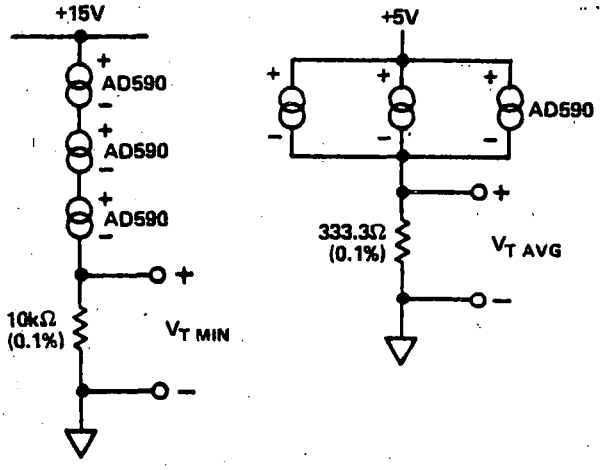


Figure 11. Series & Parallel Connection

Connecting several AD590 units in series as shown in Figure 11 allows the minimum of all the sensed temperatures to be indicated. In contrast, using the sensors in parallel yields the average of the sensed temperatures.

The circuit of Figure 12 demonstrates one method by which differential temperature measurements can be made. R_1 and R_2 can be used to trim the output of the op amp to indicate

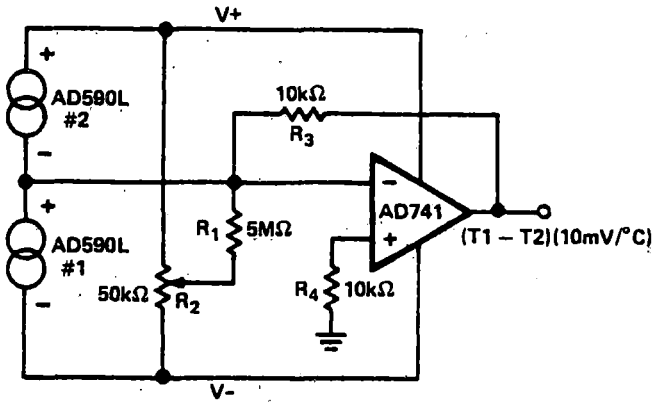


Figure 12. Differential Measurements

a desired temperature difference. For example, the inherent offset between the two devices can be trimmed in. If V+ and V– are radically different, then the difference in internal dissipation will cause a differential internal temperature rise. This effect can be used to measure the ambient thermal resistance seen by the sensors in applications such as fluid level detectors or anemometry.

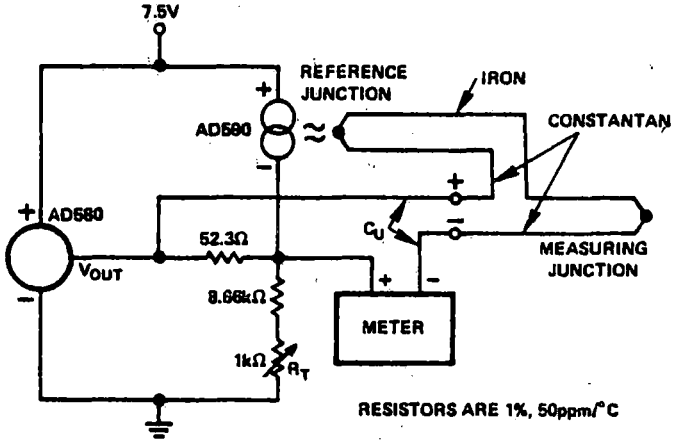


Figure 13. Cold Junction Compensation Circuit for Type J Thermocouple

Figure 13 is an example of a cold junction compensation circuit for a Type J Thermocouple using the AD590 to monitor the reference junction temperature. This circuit replaces an ice-bath as the thermocouple reference for ambient temperatures between +15°C and +35°C. The circuit is calibrated by adjusting R_T for a proper meter reading with the measuring junction at a known reference temperature and the circuit near +25°C. Using components with the T.C.'s as specified in Figure 13, compensation accuracy will be within ±0.5°C for circuit temperatures between +15°C and +35°C. Other thermocouple types can be accommodated with different resistor values. Note that the T.C.'s of the voltage reference and the resistors are the primary contributors to error.

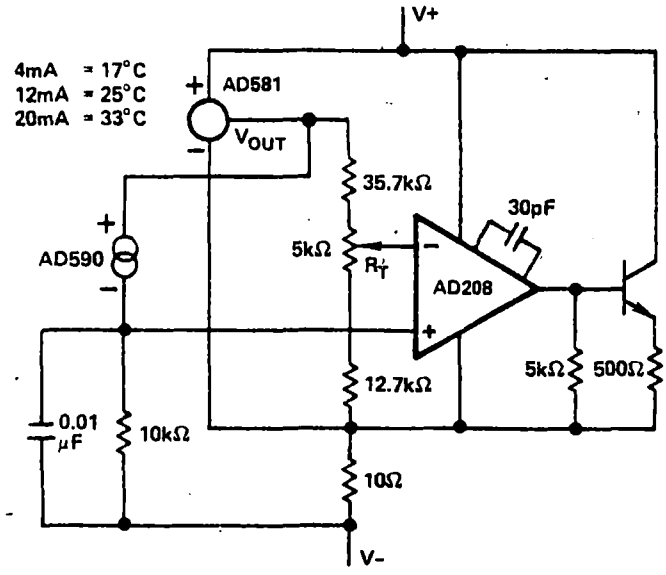


Figure 14. 4 to 20mA Current Transmitter

Figure 14 is an example of a current transmitter designed to be used with 40V, 1kΩ systems; it uses its full current range of 4mA to 20mA for a narrow span of measured temperatures. In this example the 1μA/°K output of the AD590 is amplified to 1mA/°C and offset so that 4mA is equivalent to 17°C and 20mA is equivalent to 33°C. R_T is trimmed for proper reading at an intermediate reference temperature. With a suitable choice of resistors, any temperature range within the operating limits of the AD590 may be chosen.

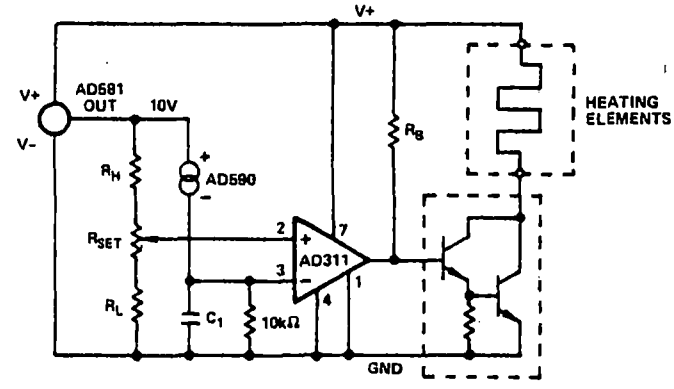


Figure 15. Simple Temperature Control Circuit

Figure 15 is an example of a variable temperature control circuit (thermostat) using the AD590. R_H and R_L are selected to set the high and low limits for R_{SET}. R_{SET} could be a simple pot, a calibrated multi-turn pot or a switched resistive divider. Powering the AD590 from the 10V reference isolates the AD590 from supply variations while maintaining a reasonable voltage (~7V) across it. Capacitor C_1 is often needed to filter extraneous noise from remote sensors. R_B is determined by the β of the power transistor and the current requirements of the load.

Figure 16 shows how the AD590 can be configured with an 8 bit DAC to produce a digitally controlled setpoint. This

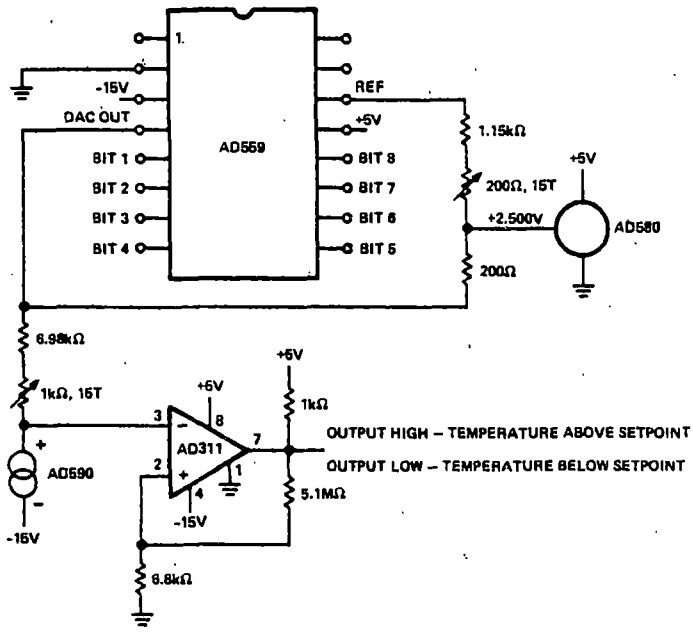


Figure 16. DAC Setpoint

particular circuit operates from 0 (all inputs high) to +51°C (all inputs low) in 0.2°C steps. The comparator is shown with 1°C hysteresis which is usually necessary to guard-band for extraneous noise; omitting the 5.1MΩ resistor results in no hysteresis.

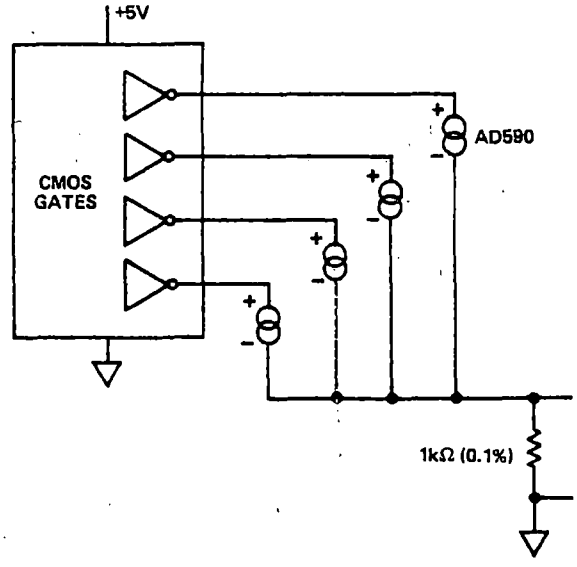


Figure 17. AD590 Driven from CMOS Logic

The voltage compliance and the reverse blocking characteristic of the AD590 allows it to be powered directly from +5V CMOS logic. This permits easy multiplexing, switching or pulsing for minimum internal heat dissipation. In Figure 17 any AD590 connected to a logic high will pass a signal current through the current measuring circuitry while those connected to a logic zero will pass insignificant current. The outputs used to drive the AD590's may be employed for other purposes, but the additional capacitance due to the AD590 should be taken into account.

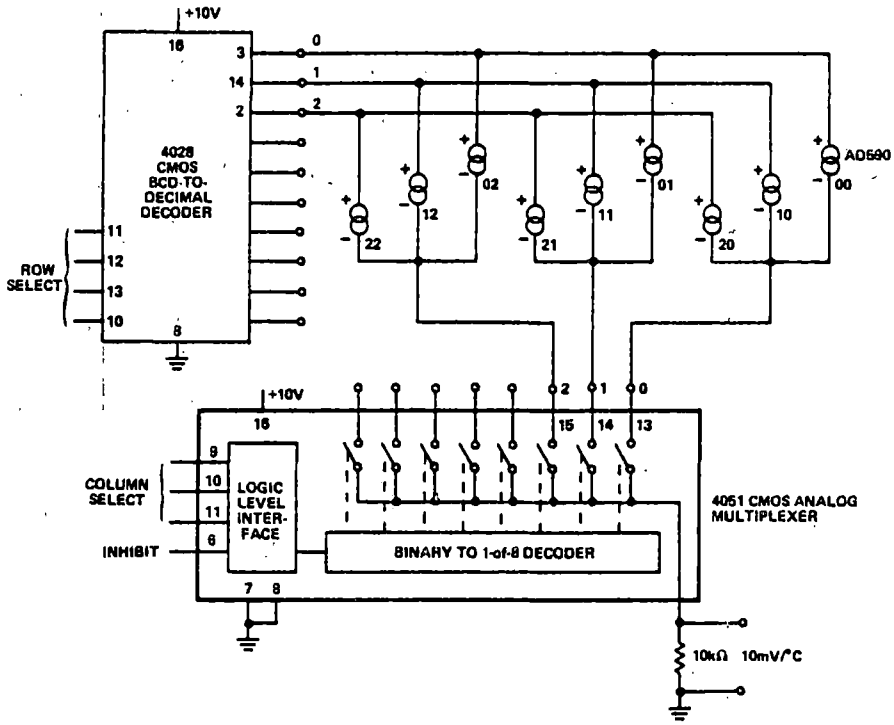


Figure 18. Matrix Multiplexer

CMOS Analog Multiplexers can also be used to switch AD590 current. Due to the AD590's current mode, the resistance of such switches is unimportant as long as 4V is maintained across the transducer. Figure 18 shows a circuit which combines the principal demonstrated in Figure 17 with an 8 channel CMOS Multiplexer. The resulting circuit can select one of eighty sensors over only 18 wires with a 7 bit binary word. The inhibit input on the multiplexer turns all sensors off for minimum dissipation while idling.

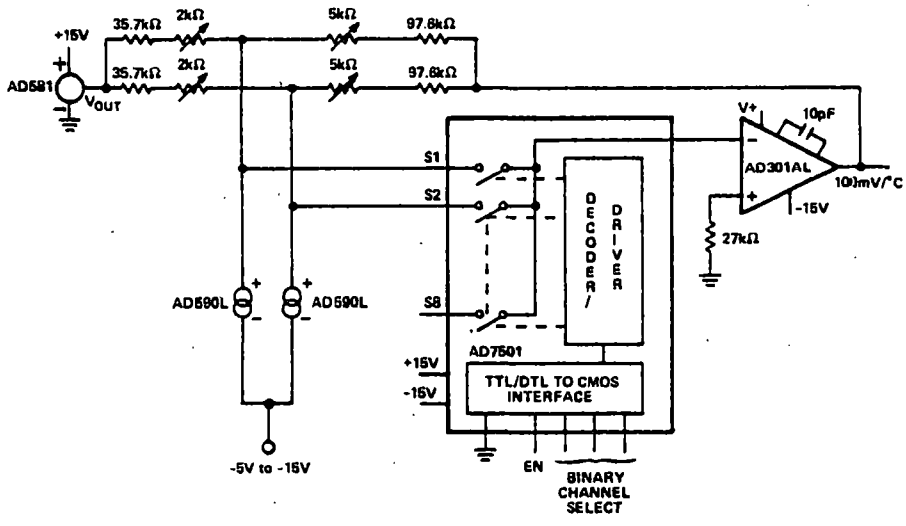


Figure 19. 8-Channel Multiplexer

Figure 19 demonstrates a method of multiplexing the AD590 in the two-trim mode (Figure 7). Additional AD590's and their associated resistors can be added to multiplex up to 8 channels of ±0.5°C absolute accuracy over the temperature range of −55°C to +125°C. The high temperature restriction of +125°C is due to the output range of the op amps; output to +150°C can be achieved by using a +20V supply for the op amp.

ANALOG DEVICES

APPLICATION NOTE

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ACCURACIES OF THE AD590

The following tables contain maximum errors by grade for applications involving limited temperature spans. The tables reflect the worst-case nonlinearities of the AD590, which invariably occur at the ends of the specified temperature range. The "trims" in each table refer to the error correction circuits on pages 4 and 5 of the AD590 Data Sheet (Figures 4 and 7a). All accuracies given below are ±°C. For example, if ±1°C accuracy is required over the +25°C to +75°C range, then trimming a J grade device using the circuit of Figure 4 on the AD590 Data Sheet will result in a sensor of the required accuracy and range.

M GRADE

Number Of Trims	Temperature Span (°C)	Lowest Temperature In Span (°C)							
		-55	-25	0	+25	+50	+75	+100	+125
None	10	0.6	0.5	0.6	0.6	0.7	0.7	0.7	0.9
None	25	0.8	0.8	0.7	0.7	0.8	0.8	1.0	1.1
None	50	1.0	0.9	0.8	0.9	0.9	1.1	1.2	–
None	100	1.3	1.4	1.3	1.4	1.5	–	–	–
None	150	1.5	1.6	1.6	–	–	–	–	–
None	205	1.7	–	–	–	–	–	–	–
One	10	0.2	0.1	0.1	0.1	0.1	0.1	0.1	0.2
One	25	0.4	0.3	0.2	0.2	0.2	0.2	0.3	0.4
One	50	0.5	0.4	0.3	0.3	0.3	0.4	0.5	–
One	100	0.8	0.8	0.7	0.7	0.8	–	–	–
One	150	0.9	0.9	0.9	–	–	–	–	–
One	205	1.0	–	–	–	–	–	–	–
Two	10	0.1	*	*	*	*	*	*	0.1
Two	25	0.1	*	*	*	*	*	*	0.1
Two	50	0.2	*	*	*	*	*	0.2	–
Two	100	0.2	0.1	*	0.1	0.2	–	–	–
Two	150	0.3	0.2	0.3	–	–	–	–	–
Two	205	0.3	–	–	–	–	–	–	–

*Below ±0.05°C

L GRADE

Number Of Trims	Temperature Span (°C)	Lowest Temperature In Span (°C)							
		-55	-25	0	+25	+50	+75	+100	+125
None	10	1.0	1.0	1.1	1.1	1.2	1.3	1.4	1.6
None	25	1.3	1.3	1.3	1.4	1.5	1.6	1.7	1.9
None	50	1.9	1.8	1.7	1.8	1.9	2.1	2.4	–
None	100	2.4	2.4	2.4	2.4	2.7	–	–	–
None	150	2.7	2.6	2.8	–	–	–	–	–
None	205	3.0	–	–	–	–	–	–	–
One	10	0.2	0.1	0.1	0.1	0.1	0.1	0.1	0.2
One	25	0.5	0.4	0.3	0.3	0.3	0.3	0.4	0.5
One	50	1.0	0.8	0.6	0.6	0.6	0.8	1.0	–
One	100	1.3	1.2	1.1	1.1	1.3	–	–	–
One	150	1.4	1.3	1.4	–	–	–	–	–
One	205	1.6	–	–	–	–	–	–	–
Two	10	0.1	*	*	*	*	*	*	0.1
Two	25	0.1	*	*	*	*	*	*	0.1
Two	50	0.2	*	*	*	*	*	0.2	–
Two	100	0.3	0.2	0.1	0.2	0.3	–	–	–
Two	150	0.3	0.2	0.3	–	–	–	–	–
Two	205	0.4	–	–	–	–	–	–	–

*Below ±0.05°C

K GRADE

Number Of Trims	Temperature Span (°C)	Lowest Temperature In Span (°C)							
		-55	-25	0	+25	+50	+75	+100	+125
None	10	2.1	2.3	2.5	2.7	2.9	3.1	3.3	3.6
None	25	2.6	2.7	2.8	3.0	3.2	3.5	3.8	4.2
None	50	3.8	3.5	3.4	3.6	3.8	4.3	5.1	–
None	100	4.2	4.3	4.4	4.6	5.1	–	–	–
None	150	4.8	4.8	5.3	–	–	–	–	–
None	205	5.5	–	–	–	–	–	–	–
One	10	0.2	0.1	0.1	0.1	0.1	0.1	0.1	0.2
One	25	0.6	0.4	0.3	0.3	0.3	0.4	0.5	0.6
One	50	1.2	1.0	0.7	0.7	0.7	1.0	1.2	–
One	100	1.5	1.4	1.3	1.3	1.5	–	–	–
One	150	1.7	1.5	1.7	–	–	–	–	–
One	205	2.0	–	–	–	–	–	–	–
Two	10	0.1	*	*	*	*	*	*	0.1
Two	25	0.2	0.1	*	*	*	*	0.1	0.2
Two	50	0.3	0.1	*	*	*	0.1	0.2	–
Two	100	0.5	0.3	0.2	0.3	0.7	–	–	–
Two	150	0.6	0.5	0.7	–	–	–	–	–
Two	205	0.8	–	–	–	–	–	–	–

*Below ±0.05°C

J GRADE

Number Of Trims	Temperature Span (°C)	Lowest Temperature In Span (°C)							
		-55	-25	0	+25	+50	+75	+100	+125
None	10	4.2	4.6	5.0	5.4	5.8	6.2	6.6	7.2
None	25	5.0	5.2	5.5	5.9	6.0	6.9	7.5	8.0
None	50	6.5	6.5	6.4	6.9	7.3	8.2	9.0	–
None	100	7.7	8.0	8.3	8.7	9.4	–	–	–
None	150	9.2	9.5	9.6	–	–	–	–	–
None	205	10.0	–	–	–	–	–	–	–
One	10	0.3	0.2	0.2	0.2	0.2	0.2	0.2	0.3
One	25	0.9	0.6	0.5	0.5	0.5	0.6	0.8	0.9
One	50	1.9	1.5	1.0	1.0	1.0	1.5	1.9	–
One	100	2.3	2.2	2.0	2.0	2.3	–	–	–
One	150	2.5	2.4	2.5	–	–	–	–	–
One	205	3.0	–	–	–	–	–	–	–
Two	10	0.1	*	*	*	*	*	*	0.1
Two	25	0.2	0.1	*	*	*	*	0.1	0.2
Two	50	0.4	0.2	0.1	*	*	0.1	0.2	*
Two	100	0.7	0.5	0.3	0.7	1.0	–	–	–
Two	150	1.0	0.7	1.2	–	–	–	–	–
Two	205	1.5	–	–	–	–	–	–	–

*Below ±0.05°C

I GRADE

Number of Trims	Temperature Span (°C)	Lowest Temperature In Span (°C)							
		-55	-25	0	+25	+50	+75	+100	+125
None	10	8.4	9.2	10.0	10.8	11.6	12.4	13.2	14.4
None	25	10.0	10.4	11.0	11.8	12.0	13.8	15.0	16.0
None	50	13.0	13.0	12.8	13.8	14.6	16.4	18.0	–
None	100	15.2	16.0	16.6	17.4	18.8	–	–	–
None	150	18.4	19.0	19.2	–	–	–	–	–
None	205	20.0	–	–	–	–	–	–	–
One	10	0.6	0.4	0.4	0.4	0.4	0.4	0.4	0.6
One	25	1.8	1.2	1.0	1.0	1.0	1.2	1.6	1.8
One	50	3.8	3.0	2.0	2.0	2.0	3.0	3.8	–
One	100	4.8	4.5	4.2	4.2	5.0	–	–	–
One	150	5.5	4.8	5.5	–	–	–	–	–
One	205	5.8	–	–	–	–	–	–	–
Two	10	0.3	0.2	0.1	*	*	0.1	0.2	0.3
Two	25	0.5	0.3	0.2	*	0.1	0.2	0.3	0.5
Two	50	1.2	0.6	0.4	0.2	0.2	0.3	0.7	–
Two	100	1.8	1.4	1.0	2.0	2.5	–	–	–
Two	150	2.6	2.0	2.8	–	–	–	–	–
Two	205	3.0	–	–	–	–	–	–	–

*Below ±0.05°C

NOTES:

1. All accuracies excluding the 205°C span are guaranteed, not tested; the 205°C span accuracies are tested for by testing each device at -55°C, +25°C, +125°C and +150°C.

2. All one-trim accuracies excluding the 205°C span assume that the trim is made at the midpoint in the span; the 205°C span assumes a trim at +25°C.

3. All two-trim accuracies excluding the 205°C span assume that the trims are made at the endpoints of the span; the 205°C span assumes that trims are made at approximately 0°C and +140°C.

4. All accuracies exclude:
   a. Trim error in calibration technique used;
   b. Repeatability error;
   c. Long term drift errors.

In precision applications the actual errors encountered are usually dependent upon sources of error which are often overlooked in error budgets.

A) *Trim Error* is usually the largest error source. This error arises from such sources as:
   1. poor thermal coupling between the device to be calibrated and the reference sensor;
   2. reference sensor errors;
   3. device to be calibrated is not permitted to thermally settle;
   4. θ_{CA} is radically different for the trim and the application.

B) *Repeatability Errors* arise from a strain hysteresis of the package. The magnitude of this error is solely a function of the magnitude of the temperature span over which the device is used. For example, thermal shocks between 0°C and 100°C will result in an extremely low hysteresis, for a repeatability error of less than ±0.05°C. When the thermal shocks are widened to -55°C and +150°C, the device will typically exhibit a repeatability of ±0.05°C, with ±0.10°C maximum being guaranteed.

C) *Long term drift errors* are related to the average operating temperature and the magnitude of the thermal shocks experienced by the device. Extended use of the device at temperatures above 100°C typically results in a long term drift of ±0.03°C; the guaranteed maximum is ±0.10°C. Operating temperatures below 100°C induce no measurable drifts in the device. In addition to operating temperature the severity of the thermal shocks incurred will determine the absolute stability of the device. For thermal shock spans of less than 100°C, the drift is difficult to measure (<0.03°C). However, for 200°C spans the device may drift by as much as ±0.10°C after 20 such shocks. If severe, quick shocks are necessary in the application of the device, simulated life tests are recommended for a thorough evaluation of the error introduced by such shocks.

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